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CONCRETE BLOCK PAVEMENTS

by

Raymond S. Rollings
Geotechnical Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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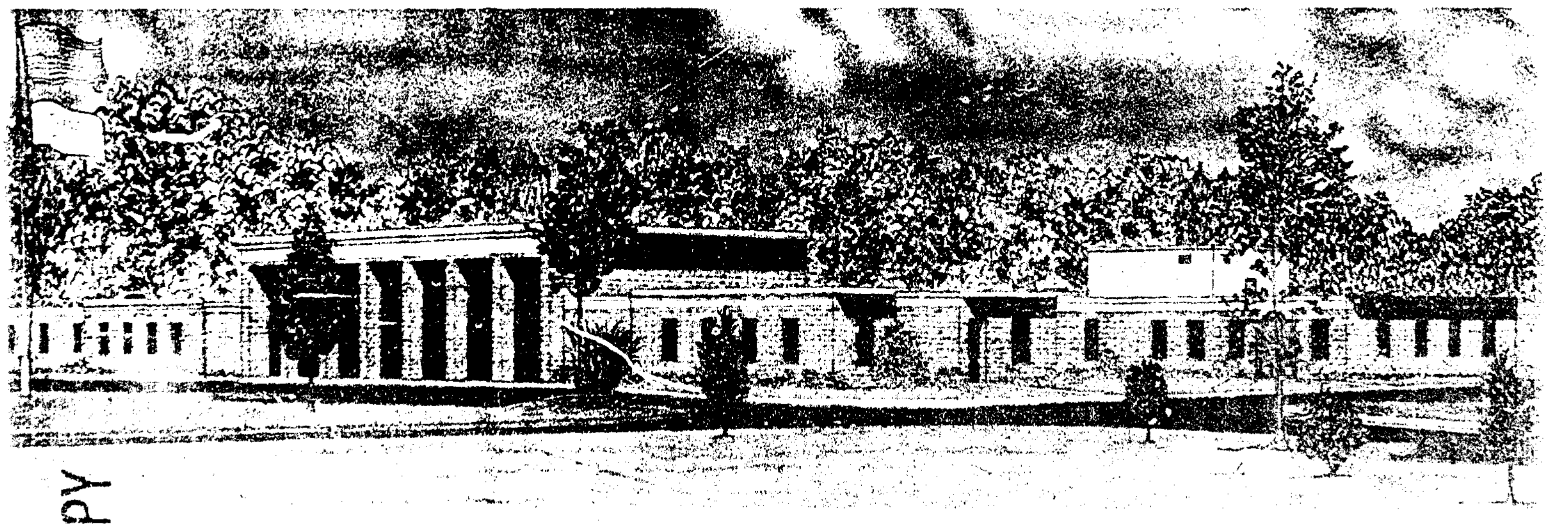

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This report reviews available literature on concrete paving blocks and describes an accelerated traffic test of three paving block test items conducted at the U. S. Army Engineer Waterways Experiment Station. This information is analyzed to develop recommendations on specifications and design methods for block pavements for use by the U. S. Army Corps of Engineers.

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20. ABSTRACT (Continued).

In general concrete block pavements behave as flexible pavements, and designs may be developed from modifications to existing flexible pavement design methods. Because of the superior load distributing characteristics of block pavements in comparison to conventional asphaltic concrete surfaces, these designs will be conservative. Both rectangular and shaped, interlocking blocks may be used in pavements. Concrete block pavements are acceptable as low speed road and industrial surfacings, are capable of supporting heavy and abrasive loads, require little maintenance, and offer easy subsurface access for utility repair or corrections for settlement.

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PREFACE

This investigation was conducted by the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), during the period November 1978-September 1980. The study was sponsored by the Office, Chief of Engineers, U. S. Army, under Project No. 4A161102AT22, Task Area AO, Work Unit 005, "Analysis of Precast Articulated Pavement System Units."

This study was conducted under the general supervision of Mr. J. P. Sale, former Chief, GL, Dr. W. F. Marcuson III, Chief, GL, Mr. A. H. Joseph, former Chief, Pavement Systems Division (PSD), GL, and Dr. T. D. White, Chief, PSD. The study was conducted by Mr. R. S. Rollings, PSD.

Commanders and Directors of WES during this investigation and preparation and publication of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic yards	0.7645549	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	2.54	centimetres
kips (force)	4.448222	kilonewtons
miles per hour (U. S. statute)	1.609347	kilometres per hour
pounds (force)	4.448222	newtons
pounds (force) per cubic foot	157.0874585	newtons per cubic metre
pounds (force) per cubic inch	0.271447	newtons per cubic metre
pounds (force) per cubic yard	5.8180544	newtons per cubic metre
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
square feet	0.09290304	square metres
square inches	6.4516	square centimetres
square yards	0.8361274	square metres
tons (force)	8896.444	newtons

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

CONCRETE BLOCK PAVEMENTS

PART I: INTRODUCTION

Background

1. Concrete block pavements are an established pavement surfacing that competes successfully with conventional portland cement concrete and asphaltic concrete in Europe for many uses. In the United States the concrete paving block industry is relatively new but is growing. The U. S. Army Corps of Engineers (CE) has used paving block in Europe and on at least one project in Florida in the United States. Use of block paving in the United States and in Corps projects may increase in the future, but there is little information available to the CE on the design, construction, and performance of block pavements.

Scope

2. This report summarizes available information on solid, concrete block pavement, describes several installations of paving block, and reports the results of an accelerated traffic test of block pavement conducted by the Geotechnical Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES). This information is used to recommend design procedures, specifications, and areas for further work with block pavements.

Description

3. A block pavement consists of dense, accurately dimensioned concrete blocks which fit closely together to form a pavement surface. The blocks are manufactured in a wide variety of shapes, some of which are shown in Figure 1. Generally the blocks are about the size of a common brick with a thickness of 2-3/8 to 4 in.* and weigh about 9 to 12 lb

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

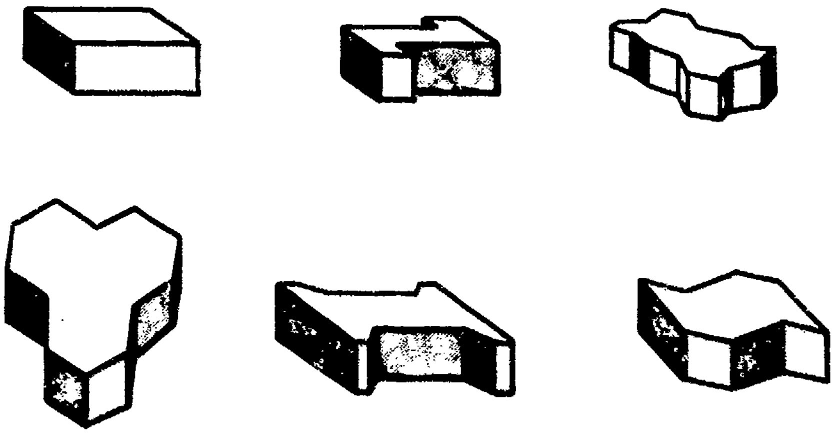


Figure 1. Examples of paving block shapes

each. A thin, 1- to 2-in.-thick leveling course of sand is used under the blocks. The blocks are generally laid by hand on this sand layer. The blocks are then compacted with a manually operated vibratory plate compactor which seats the blocks in the sand layer, compacts the sand layer, and forces some sand into the joints between blocks. Additional sand is then swept into the joints between the blocks, and more passes are made with the vibratory plate compactor to compact and wedge this sand into the joints. A base and subbase course under the leveling course provide structural support similar to that of a conventional flexible pavement. Figure 2 shows a generalized cross section of a block pavement. Many different patterns of laying blocks are possible, and several patterns are illustrated in Figure 3.

4. The solid concrete paving blocks are also commonly called "pavers," "interlocking paving stone," "road stones," or "interlocking paving block." The different shapes of paving block are often identified by manufacturers' trade names such as "Unistone," "Finetta," "Z Paver," etc.

5. Several manufacturers also produce concrete grid paving blocks. These grid paving blocks are generally 16 by 24 in. or 24 by 24 in. and 4 in. deep with various sizes, patterns, and shapes of openings in the surface. The open spaces in the stone are filled with top soil, seeded, and grass partially covers the block. Grid paving blocks are intended

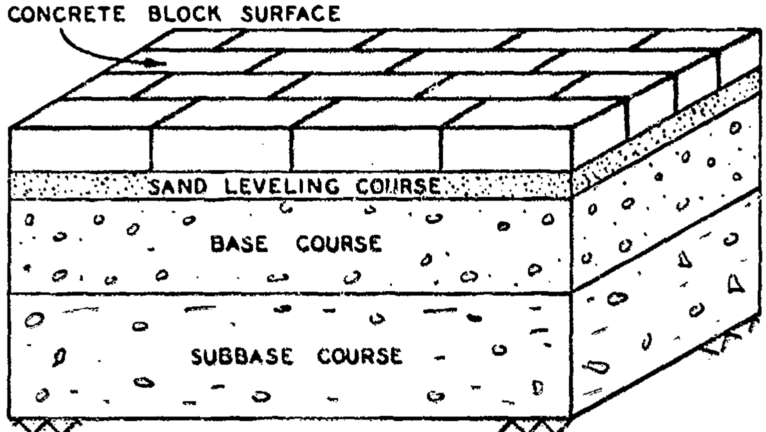
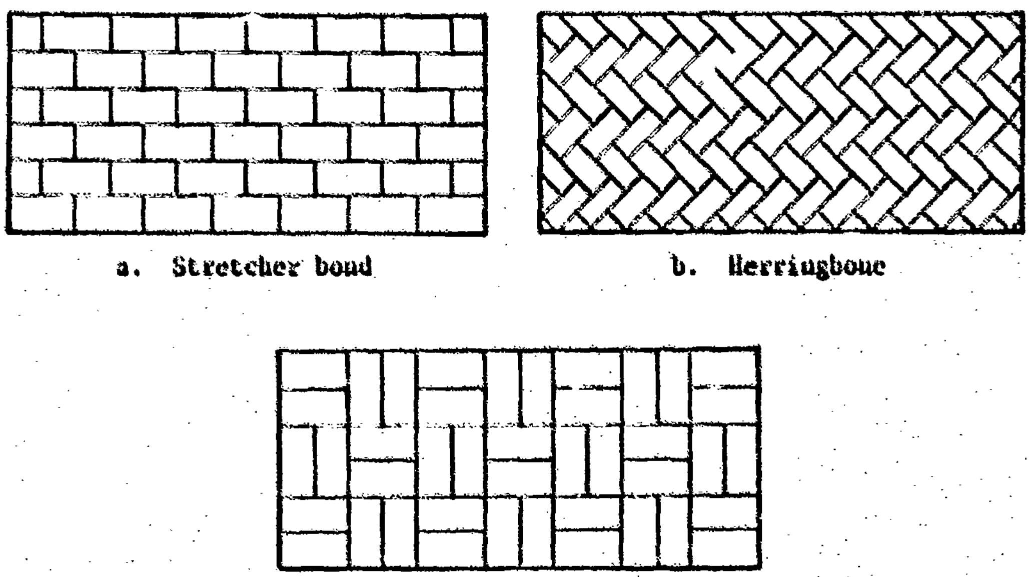


Figure 2. Cross section of a block pavement



a. Stretcher bond

b. Herringbone

c. Parquet

Figure 3. Examples of common laying patterns

for light traffic. Both solid and grid concrete paving block have also been used for erosion control. This study considers only solid concrete paving block used for pavements. Low strength concrete blocks (patio blocks, etc.) intended only for pedestrian traffic will not be covered in this report. In 1979, nine city blocks of Chicago's State Street were repaved for pedestrian traffic with hexagonal asphalt blocks (Asphalt Institute 1979), and similar asphalt blocks were used for paving an open area at the University of Maryland. Asphalt paving blocks will not be covered in this report.

Historical Development

6. Stone blocks, bricks, cobbles, and composite wood and tar units were used for road surfacings up to World War I. After this time, these paving units largely disappeared due to increased construction costs, surface smoothness requirements, and the availability of more economical, less labor intensive alternatives. Manufacturing technology in the 1950's allowed mass production of accurately dimensioned, high-strength concrete blocks and several paving block designs were introduced in Europe during this time. Europe has a long history of paving with individual stone blocks, and the concrete block pavements were readily accepted in continental Europe.

7. Small modular paving elements have been used in Amsterdam since the Middle Ages with natural stone in the carriageways to resist abrasion from steel wheels and sleds and bricks in pedestrian areas (Kellersmann 1980). As rubber tires became common at the end of the nineteenth century, bricks replaced the more expensive stone in the carriageways. The Waalformat brick, 7.7 by 3.3 by 1.9 in. (195 by 85 by 48 mm) became the most common paving unit, but as the character of vehicular traffic changed, the thickness grew progressively from 1.9 in. (48 mm) to 2.5 in. (64 mm) and then 3.6 in. (92 mm). After World War II the supply of traditional bricks failed to keep up with demand and by 1955 only half of the demand for paving bricks could be met (Kellersmann 1980). In 1951 the concrete products company Holland began production

of a rectangular concrete paving block and was followed in 1952 by the Schokbeton Company with an I-shaped concrete paving block (Van der Vlist 1980). The concrete paving block was readily accepted as a substitute for the scarce paving brick and today has essentially replaced it due to much lower costs. Since 1960 the Netherlands paving block industry has been highly mechanized and automated, and as can be seen in Figure 4, its growth has been steady (Van der Vlist 1980).

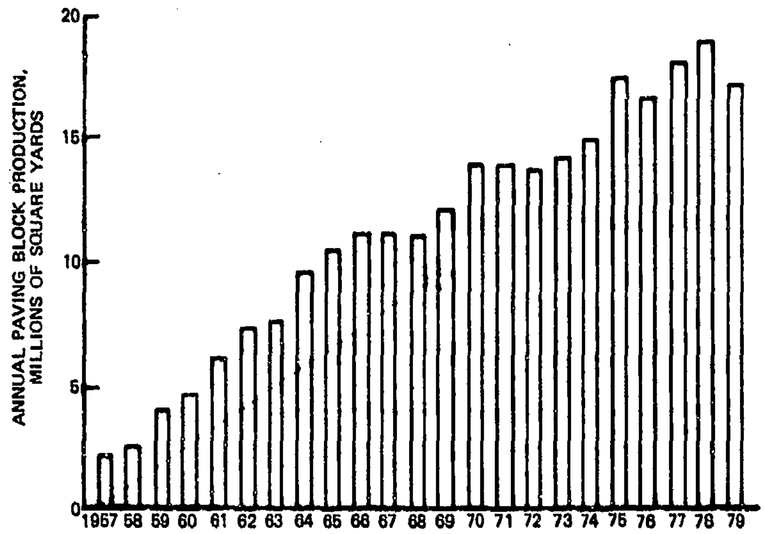


Figure 4. Concrete paving block production in the Netherlands (Van der Vlist 1980)

8. The use of concrete paving block in the Netherlands developed naturally from existing pavement practices and construction procedures. Consequently, it has never been perceived as a novel or new product and has always been readily accepted. To a somewhat lesser extent this was true throughout continental Europe, and the concrete paving block industry has developed strongly in this area, particularly in the Netherlands, the Federal Republic of Germany, and Denmark.

9. The first British concrete paving blocks were produced in 1968 under a German license but were generally limited to architectural roles. The United Kingdom (UK) Cement and Concrete Association (CCA) conducted a test and evaluation program of paving block and studied the continental European paving block industry to try to widen paving block

use in the U.K. (Knapton and Barber 1980, Knapton and Lilley 1975). A large promotion and education program in 1976 successfully increased the use of paving block in road and industrial construction in the United Kingdom. South Africa, Australia, and Canada also have growing concrete block paving industries.

10. The United States has used brick, stone, and wood for road surfacings since colonial times, and many of these old road surfacings still exist in historic districts of many cities. Bricks were used as a pavement surfacing as early as 1832 and remained competitive until after World War I (Wiley 1919). They were gradually displaced by portland cement and asphaltic concrete pavements. Concrete paving blocks were first produced in the United States in the 1960's using German equipment and designs. Today there are a number of manufacturers producing paving block, and trade associations, such as the National Concrete Masonry Association (NCMA) and Interlocking Paving Manufacturers Association (IPMA), are involved in promotional and educational programs for concrete paving block. The American Society for Testing and Materials (ASTM) is also preparing a standard specification for concrete paving blocks, but concrete paving blocks are still widely considered as a new paving material in the U. S.

Applications

11. The aesthetic value of concrete paving blocks is generally recognized, but they also provide a high-strength surface which is resistant to environmental damage and is capable of supporting large concentrated loads and heavy traffic under abrasive conditions and which is resistant to environmental damage. Because of the modular structure, blocks can be removed from the surface to allow access to subsurface utilities, or to correct settlement of underlying material. Ninety to ninety-five percent of the original blocks can then be used to resurface the pavement.

12. Block pavements have higher initial costs than conventional pavements. The same cost relation may not hold for life-cycle costs

that include the reduced maintenance costs of concrete paving blocks. Not enough data are currently available to adequately evaluate life-cycle costs of block pavements in the United States. The surface of a block pavement is rougher than conventional pavements, and this effectively limits maximum vehicular speeds to less than 40 mph.

13. In Europe paving blocks find their major use in low-speed road pavements and industrial applications. In 1972, over two-thirds of West Germany's production of 30 million yd^2 of paving block production was used in road pavements and industrial applications. In the same year Denmark used 40 percent of its paving block production for industrial construction (Cement and Concrete Association 1976). Table 1 shows a detailed breakdown on the use of the Federal Republic of Germany's block production.

14. In the United States, the paving block market is still developing. Individual manufacturers emphasize different marketing targets. Some are concentrating on the aesthetic market, such as driveways, pool decks, and parking areas in expensive developments. At least one manufacturer is trying to develop a home owner "do-it-yourself" market. Other manufacturers are emphasizing industrial and municipal road applications, such as steel mills and resurfacing municipal roads.

PART II: MANUFACTURE OF PAVING BLOCKS

Equipment

15. Concrete block production is highly automated to mass produce the product economically. Two basic types of equipment are used to produce concrete paving blocks today: the conventional block machine and the multilayer machine.

16. The block machine is used to produce conventional concrete masonry block, but with minor modifications it can also produce concrete paving block. In this process, a dry stiff concrete is forced into molds under pressure and vibrated intensely at high frequency. The completed block then leaves the machine for initial curing. Steam curing is sometimes used. This reduces the ultimate strength of the paving block, but increases the early strength of the paving block to allow handling. After initial curing to gain strength for handling, the blocks are placed on pallets and stored while curing continues. Producing paving blocks on a conventional block machine allows a block manufacturer to supplement his conventional concrete masonry block production with paving blocks during periods of low masonry block demand. In the U. S. some block manufacturers have expanded into paving block production to keep their equipment in use.

17. The multilayer machines are specifically designed for mass production of concrete paving block. As before, a dry, stiff concrete mix is forced into molds under pressure and subjected to intense vibration. An entire array of blocks sufficient for one layer on a shipping pallet is cast at one time. After the mold is removed, a thin layer of sand is spread over the newly cast paving blocks, and then another layer of paving block is cast directly on the sand-covered lower layer. This continues until an entire pallet of approximately 8 to 10 layers of paving block is cast. If a stationary multilayer machine is being used, the pallet of paving block leaves the machine, and another pallet of blocks is cast. If a traveling multilayer machine is used, the pallet remains in place, and the machine moves on rails and casts the next

pallet of paving block adjacent to the first pallet. These paving blocks are generally air-cured and may be covered with polyethylene to prevent drying during curing. Figure 5 shows a completed polyethylene covered pallet of Z-shaped paving block produced by a multilayer machine.

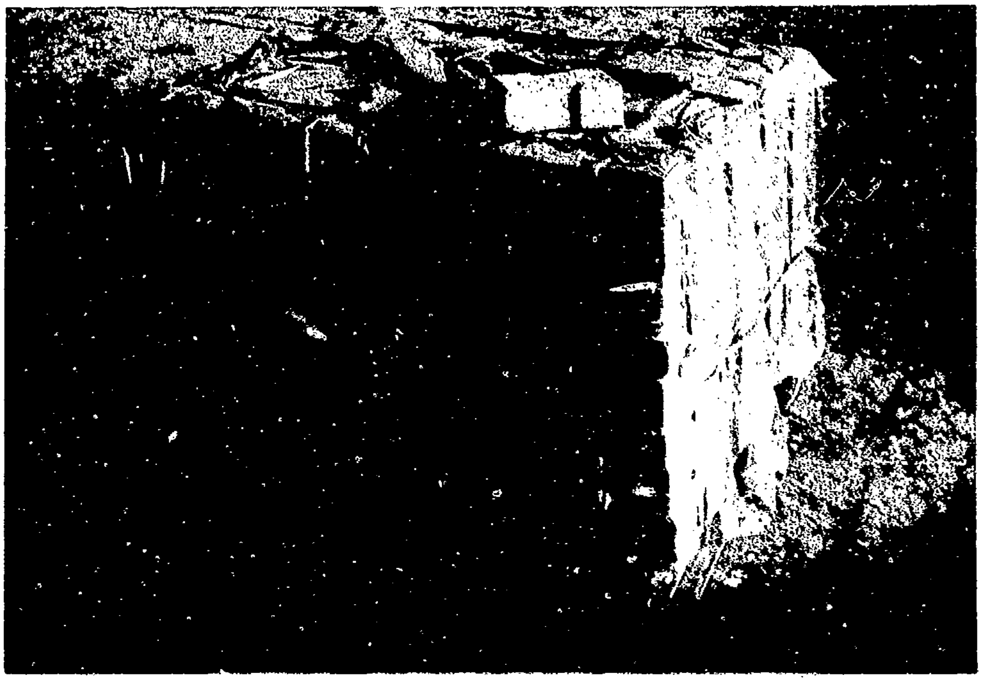


Figure 5. Finished pallet of paving block

18. Product defects can occur due to mold wear, improper mix proportioning, inadequate vibration, etc. Some examples of defective products are shown in Figure 6.

Concrete Mixture Proportioning

19. The concrete mixture used for paving block generally is dry with a water-to-cement ratio of less than 0.4 and normally contains about 14 percent Type I cement. Nominal maximum aggregate size used in paving block is generally 1/4 in. with a ratio of about 70 percent sand and 30 percent gravel. The specific proportions of any mixture will depend on available materials, machine requirements, and texture and quality of the final paving block. One U. S. manufacturer suggests an

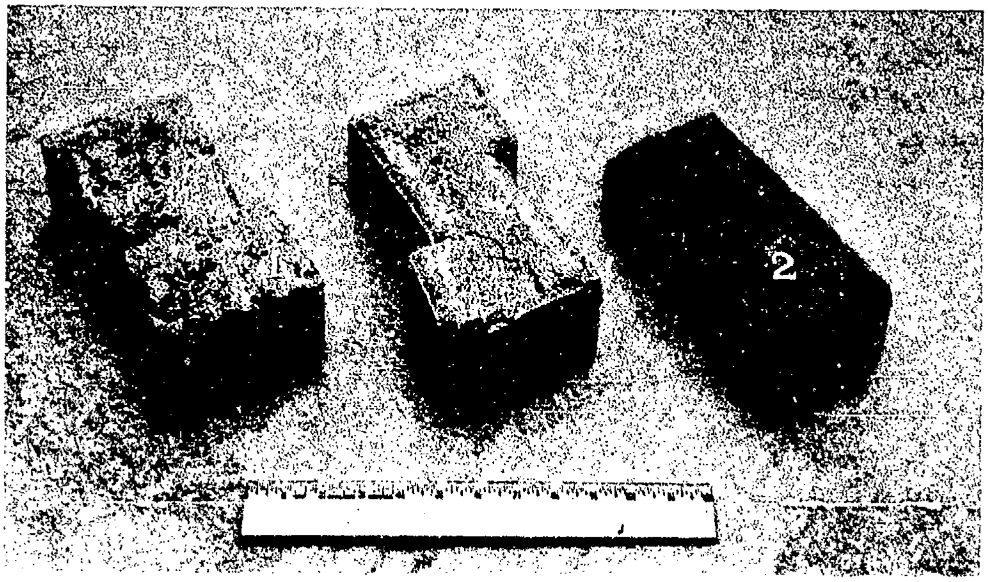


Figure 6. Defective paving blocks

initial trial mix with an aggregate fineness modulus of 3.60 to 3.65 as a starting point for proportioning the mix (Besser Company (no date)). Dawson (1980) provides a more detailed discussion on proportioning concrete mixes for paving blocks.

20. Pigments can be added to the concrete paving block mix to provide a colored product. These pigments are inert fillers generally passing the No. 350 sieve (Von Szadkowski 1980). Although organic pigments provide excellent, bright color shades, they are unstable in the alkaline concrete environment and are affected by weathering (Von Szadkowski 1980). Pigments used in paving blocks are synthetic or natural iron oxides that provide weathering stable colors such as red, yellow, buff, brown, and greyish black.

21. The color intensity of paving block can be increased up to a point by increasing the amount of pigment. Once this saturation or optimum level is reached, further additions of pigment have little effect. This condition is illustrated in Figure 7. The optimum pigment content for bright, synthetic pigments is usually about 5 percent of the cement weight with minor variations for specific colors and aggregate gradations (Von Szadkowski 1980).

22. Color pigment is inert and plays no part in the chemical

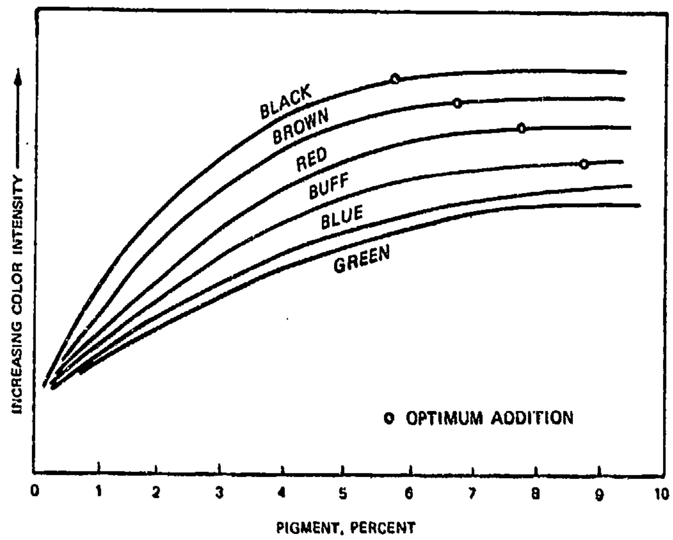


Figure 7. Effect of pigment content on color intensity (Dawson 1980)

reactions of the concrete. If the water-cement ratio of the concrete mix is kept constant, the addition of pigment will not affect the final product strength. However, as shown by the spread test in Figure 8, the workability of the mix may decrease when the pigment is added at a

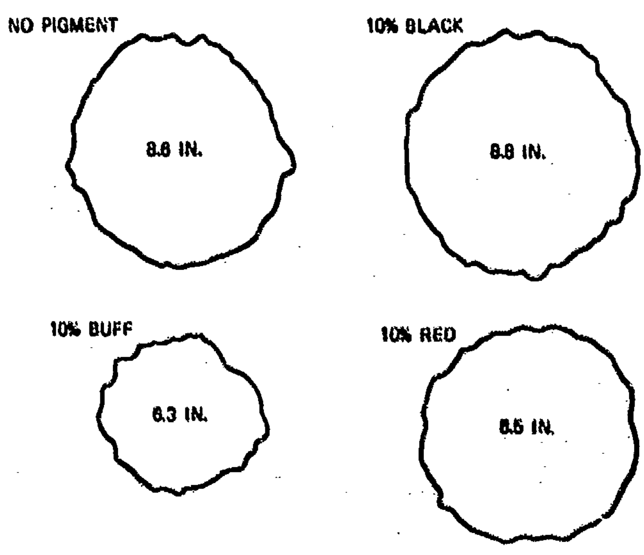


Figure 8. Effect of pigment content on spread at a constant water content (Dawson 1980)

constant water content, and this may lead to manufacturing problems such as adhesion to the manufacturing machine's rams. To restore workability, additional water may have to be added to the mix and this additional water may lead to a reduction in the block's strength.

Block Quality

23. Concrete paving blocks must have sufficient strength and durability to withstand traffic loads, abrasion, and weather conditions. They also must be manufactured to close dimensional tolerances to allow rapid construction with tight joint patterns. Various organizations have specified different test standards to ensure that paving blocks will have the required properties to perform their function, but these standards show some variation.

Strength

24. The most common requirement for blocks is a minimum strength. Table 2 compares several different paving block strength requirements from different countries. These strength requirements are high, but blocks with these strengths have an established history of good performance under severe loads. The consistent high quality of paving blocks is believed to be one reason for its rapid acceptance and growth (Kuthe 1980).

25. There is considerable disagreement over the appropriate strength test that should be used to evaluate paving blocks. Various proponents have suggested compressive, flexural, and splitting tensile tests. Paving block strength requirements will be discussed in more detail in Part VIII of this report.

Abrasion

26. A block pavement is subject to abrasive wear from traffic and a variety of abrasion tests are possible. The Netherland's standard NEN 7000 requires a sandblast abrasion test to evaluate abrasion resistance. Dreijer (1980) describes the abrasion-related problems which developed in the Netherlands in 1968 and the resulting investigation and changes in the NEN 7000 standard that were made to avoid these problems

in the future. This investigation found a direct relationship between the weight loss in the sandblast test and the block flexural strength, but blocks with a thin abrasion vulnerable surface layer could not be identified by strength alone. This thin layer generally developed from curing techniques, improper plasticity of the concrete mix, or decorative finishing. The sandblast test was effective in identifying these thin abrasion-susceptible layers.

27. The German standard DIN 18501 on paving blocks issued in 1964 included a requirement for a mechanical grinding test to evaluate abrasion resistance. A proposed revision to DIN 18501 will drop this requirement because experience has shown that blocks with the required compressive strength of 8700 psi are sufficiently abrasion resistant (Meyer 1980).

28. There are a variety of abrasion tests available for concrete such as sandblast tests, rattler-type tests, or mechanical abrasion tests with disks, wheels, or steel balls. However, these tests only allow an evaluation of relative quality without any defined acceptable criteria for wear of concrete surfaces (Lane 1978). Concrete abrasion resistance is affected by a variety of factors, but concrete compressive strength has been widely used as an abrasion criterion and is used to set abrasion resistance standards for industrial floors (American Concrete Institute 1969, Spears 1978). The high compressive strength of concrete paving block indicates high abrasion resistance, but evaluation only on the basis of strength will not identify the thin abrasion-susceptible block surfaces reported by Dreijer (1980).

29. An abrasion test appears to be needed in paving block specifications to identify blocks with abrasion-susceptible surfaces. The selected abrasion test may have to be modified. For example, Dreijer (1980) reports that the amount of sand used in the sandblast test was reduced from 3500 g to 1000 g so that only a thin surface layer was actually tested and not the underlying concrete. The abrasion resistance of the lower concrete could be evaluated adequately on the basis of the block strength.

Freezing and thawing

30. Deterioration can occur to nonfrost-resistant concrete when it is subject to critical saturation with water followed by freezing and thawing. If water freezes in concrete pores that are large enough to contain freezable water and that are critically filled, the expansion of the ice will try to expel water from the pore. Depending on the speed of freezing and the permeability of the cement paste, dilation pressures can develop (Neville 1973, Mather 1975, Powers 1975). Pores large enough to contain freezable water can exist in both the concrete aggregates and the cement paste. Another source of dilating pressure which can cause freezing-related concrete deterioration is the osmotic or osmoticlike pressure developed from local increases in solute concentration due to the separation of frozen water from the solution (Neville 1973, Powers 1975). This mechanism may be particularly important in concrete pavements. A concrete pavement slab which freezes from the top can be seriously damaged if water has access to the bottom of the slab and travels through the slab due to osmotic pressure (Neville 1973). The concrete moisture content can increase above its original value and segregation of ice crystals into layers has reportedly been observed in some cases (Neville 1973). The use of deicing salts is believed to further increase the solute concentration near the slab surface with a resulting increase in the osmotic pressure (Powers 1975). Paving block surfaces may be exposed to environmental and salting conditions similar to that of conventional concrete pavements.

31. The major factors that determine the resistance of concrete to freezing and thawing are the degree of saturation and the pore structure of the concrete (Neville 1973). Concrete can be protected against freezing by providing a properly air-entrained paste and using sound frost-resistant aggregate (Neville 1973, Mather 1975, Powers 1975). All paving blocks should contain sound frost-resistant aggregate; however, air entrainment is not now used in concrete paving block. The intense vibration used in paving block manufacture is claimed to cause an undesirable loss of entrained air, and Clark (1980) states that the stiff consistency of the low water-cement ratio mixtures used in paving blocks

inhibits the action of air-entraining agents and makes measurement of the air content very difficult. Therefore, the practice in Europe has been to specify a paving block strength that is hoped will provide protection against frost and deicing salts and not to use entrained air.

32. Meyer (1980) states that paving blocks that meet the 8700-psi compressive strength requirement of the German DIN 18501 and are manufactured from standard cements and frost-resistant aggregates are sufficiently durable when exposed to freezing and thawing and deicing salts. Dreijer (1980) reports that the blocks meeting the strength and sandblast test requirements of Netherlands NEN 7000 can be expected to be resistant to frost and deicing salts. If paving block will not be exposed to freezing and thawing, the United States National Concrete Masonry Association (1979) reduces the required strength from 8000 psi to 6000 psi and increases the maximum allowable absorption from 5 to 8 percent. However, they require that the durability of the paving blocks that will be exposed to freezing and thawing be established by proven field performance under similar field conditions for 3 years or by conducting a laboratory freeze-thaw test.

33. Clark (1980) describes a series of tests of concrete paving blocks that examine the effects of density, water-cement ratio, cement content, compressive strength, 24-hr absorption values, and initial surface absorption on resistance of paving blocks to freezing and thawing with deicing salts. The test specimen paving blocks were prepared with various types of aggregate, with cement contents varying from 318 lb/yd^3 to 989 lb/yd^3, and with water-cement ratios of 0.22 to 0.62. Test specimens were also made from paving quality concrete with 3 to 6 percent air and a cement content of approximately 607 lb/yd^3. All test specimens were 7.9 by 3.9 by 2.6 in. Five specimens were prepared for every mixture tested.

34. The freeze-thaw tests followed the procedures of RILEM CDC 2. The test specimens were exposed to cycles of 16 to 17 hr of freezing at -4° F and then 7 to 8 hr of thawing. Deicing solutions of 3 percent salt were maintained 0.08 to 0.18 in. deep on the block surfaces. Blocks were withdrawn from testing when the block surface had

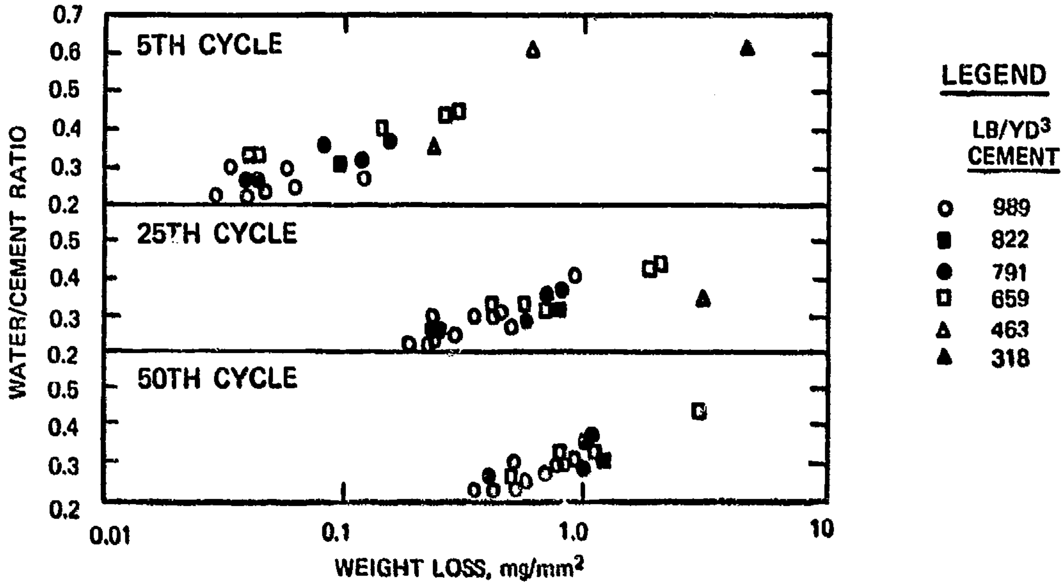


Figure 9. Relationship between water-cement ratio and weight loss (Clark 1980)

deteriorated to the point that the deicing solution could no longer be kept on the sample.

35. As shown in Figure 9, paving blocks with low water-cement ratios suffered less damage in the freeze-thaw tests than those with higher water-cement ratios. This figure also suggests that blocks with high cement contents may have outperformed those with lower cement contents, but the results are not conclusive. For a given water-cement ratio the weight loss from freezing and thawing did not change due to aggregate type used in these tests.

36. No relation between absorption and weight loss can be identified in Figure 10. Similarly, Clark (1980) found no relation between weight loss and either initial surface absorption or density. In Figure 11 the effect of compressive strength on weight loss is less clear. Samples that differed only in strength due to curing for 35 days and 9 months showed no change in weight loss, nor did the samples marked "all other paving blocks" in Figure 11. However, two points in Figure 11 marked as low-strength paving blocks suggest a strength relationship. These two low-strength results also had relatively high

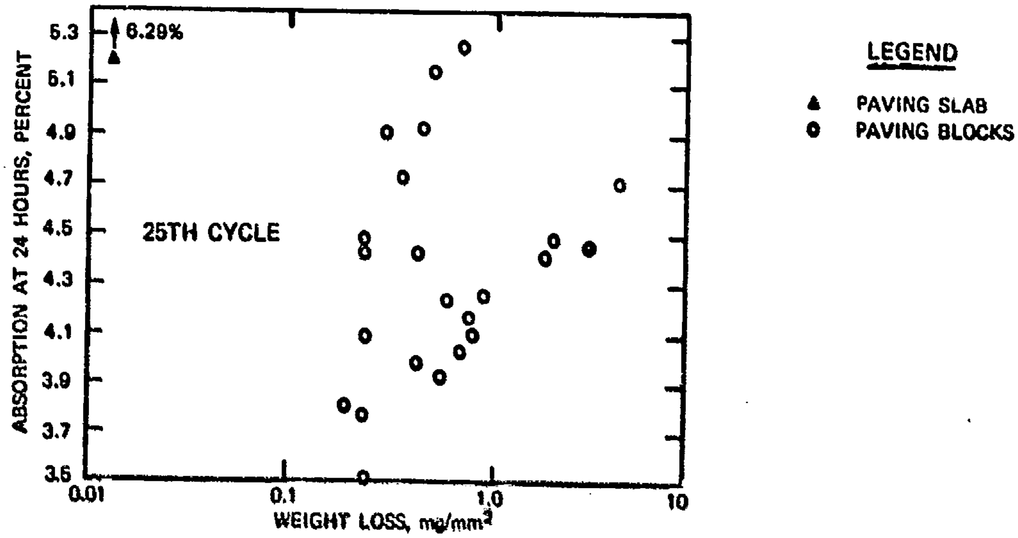


Figure 10. Relationship between absorption and weight loss (Clark 1980)

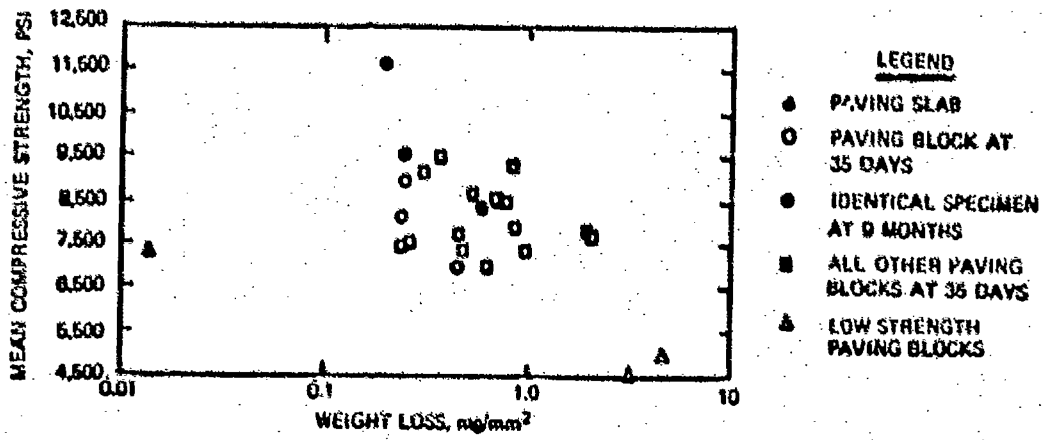


Figure 11. Relationship between mean compressive strength and weight loss (Clark 1980)

water-cement ratios of 0.36 and 0.62. As shown in Figure 9, this has an effect on weight loss. Since the increase in strength due only to curing had no effect on weight loss and these two low-strength points had high water-cement ratios, compressive strength does not appear to be a reliable indicator of weight loss for this test.

37. Current manufacturing practice produces paving block that are subject to potential freezing and thawing damage because of inadequate pore structure. However, freezing and thawing damage has not been reported as a major problem with paving blocks. The high cement content, low water-cement ratios, and manufacturing process used to produce paving blocks provide a final product that has high density and low permeability. Even though the pore structure makes paving block potentially vulnerable to freezing and thawing damage, this low permeability seems to keep the paving block pore structure from becoming critically saturated under the conditions that most paving blocks encounter in the field. Resistance to freezing and thawing damage for paving blocks cannot be set by strength or absorption limits. The block should be specified by requiring proven field performance or a laboratory freeze-thaw test.

38. An improved product could be produced by manufacturing paving block with an adequate pore structure. In conventional concrete pavements, this is provided by sound aggregates and entrained air in the cement paste. A more frost-resistant concrete paving block could be developed by providing a proper void structure through air entrainment or possibly using hollow plastic microspheres (Ozyildirim and Sprinkel 1982) or adding crushed porous material (Litvan and Sereda 1978).

Skid resistance

39. In general, skid resistance has not been a problem with concrete block pavements. The Netherlands specification NEN 7000 includes a skid resistance test with the Leroux pendulum laboratory apparatus (Dreijer 1980). In the United Kingdom the paving block fine aggregate cannot contain more than 25 percent acid-soluble material (Dawson 1980). This requirement avoids materials that polish easily under traffic with a resulting decrease in paving block skid resistance. This has been

found to be a particular problem with sea dredged material containing shells.

Dimensional tolerances

40. Paving blocks must be manufactured to close dimensional tolerances to simplify construction, provide tight joints, and ensure load-carrying and distributing properties of the completed pavements. Allowable deviations in length and width measurements vary from 0.118 in. (3 mm) in the German specification DIN 18501 to 0.059 in. (1.5 mm) in the Netherlands specifications NEN 7000. The U. S. National Concrete Masonry Association (1979) allows a deviation of 0.062 in. (2 mm). Allowable height variations are less stringent and vary from the National Concrete Masonry Association (1979) height variation of 0.125 in. (3 mm) to the DIN 18501 height of 0.197 in. (5 mm).

PART III: BLOCK PAVEMENT CONSTRUCTION

41. Concrete block pavements require a subbase or base or both just as conventional flexible pavements do. These layers are constructed and function the same for both flexible and block pavements.

42. A thin layer of sand is spread over the surface of the base course. This sand acts as a laying or bedding course for the blocks. In the United States, United Kingdom, and Australia the common practice is to leave this sand uncompacted (National Concrete Masonry Association 1979, Lilley and Collins 1976, Morrish 1980), but in other areas the sand layer may be compacted prior to placing the blocks (Kellersmann 1980, Working Committee on Concrete Block Paving 1965). Compacting the sand before placing the blocks increases the effort of block laying since the compacted sand layer will have to be screeded level again after compaction and no sand will work into the joints from the sand layer when the blocks are vibrated (Lilley 1980). The sand used in the laying course should be a clean, well graded, sharp sand with a maximum size of about 3/8 in. and a maximum of 3 percent silt or clay (National Concrete Masonry Association 1979). Two recommended gradations for this sand layer are shown in Figure 12. A cement mortar or a sand and dry cement sand laying course can be used, but generally this is not recommended unless the blocks are less than 2.4 in. thick (Meyer 1980) because the mortar would make it difficult to remove and reuse blocks and because of potential frost damage to the mortar and the extra expense of the mortar (Lilley 1980).

43. Paving blocks are set by hand as shown in Figure 13. A multitude of laying patterns are possible; several were illustrated earlier in Figure 3. Blocks are split to fit any cavities at edge of the pavement, around manholes, etc., where a whole block will not fit. A hydraulic block splitter is shown in Figure 14. Some work has been done to automate placing paving block, but such systems are not in general use now.

44. The blocks are seated in the sand-laying course by vibrating them with a vibratory plate compactor. Sand is swept from the surface, and as shown in Figures 15 and 16, vibrated into the joints between the

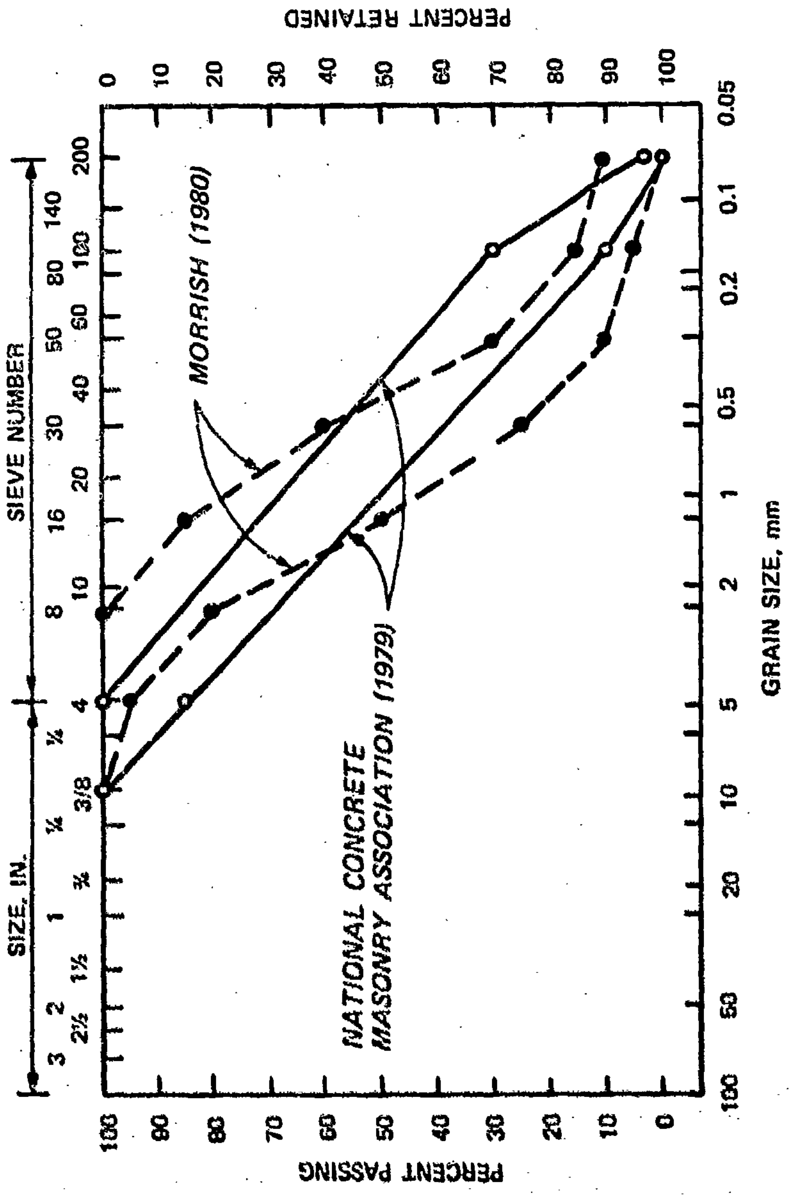


Figure 12. Recommended gradation limits for sand laying courses

Figure 13. Placing concrete paving block (Z-blocks)

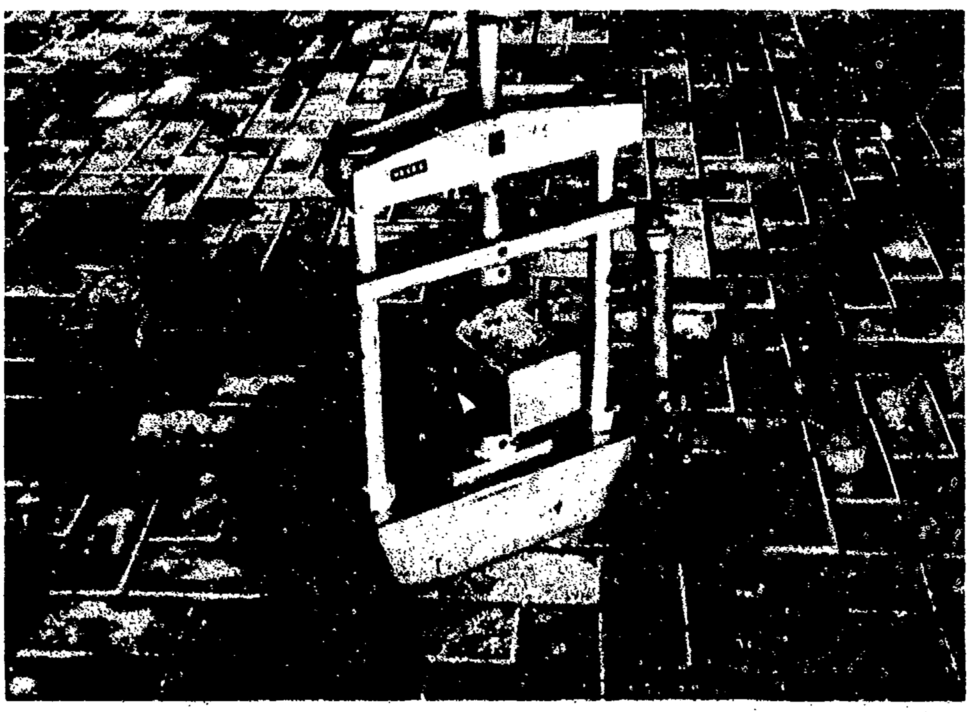


Figure 14. Hydraulic block splitter

Figure 15. Vibrating sand into paving block joints, WES test section

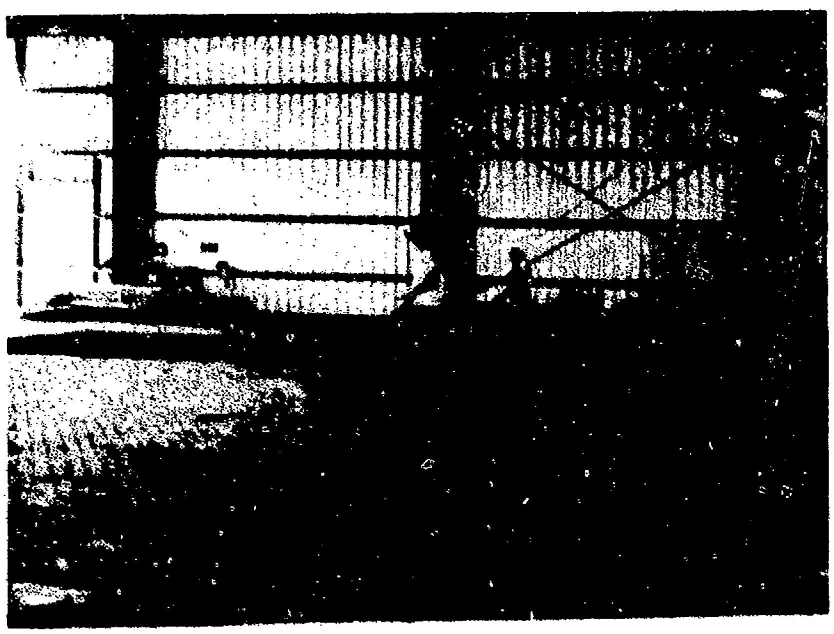


Figure 16. Vibrating sand into paving block joints, Berg Steel Pipe Plant

blocks. After the joints are tightly filled, the excess sand is swept from the surface.

45. Lilley and Collins (1976) suggest using a vibratory plate with an area of 2.15 to 3.33 ft^2 and a centrifugal force of 2,200 lb. They state that a heavy compactor will not provide any additional benefit. Kellersmann (1980) reports that a 3,300-lb vibratory roller or a 13,230-lb static roller are most commonly used in the Netherlands.

46. Lateral restraint must be provided on all sides of a block pavement. There are no test data that provide actual limits on the amount of restraint needed to keep blocks from separating under traffic.

47. Figure 17 shows the layout of a paving block work site. The

Figure 17. Construction at Berg Steel Pipe Plant

sand leveling course has been screeded out ahead of the working face. Blocks have been delivered from the pallet to the working face where they are placed by hand. Pallets of blocks are distributed down the length of the working area where they will be available as the working face of the pavement advances. Lateral edge restraint is provided by the concrete strips which will later be used for equipment foundations.

48. Block pavement can be constructed by relatively unskilled

labor. Production varies, depending on the complexity of the project and skill of the block layers. Different estimates of output on block pavement construction are shown in Table 3.

PART IV: PERFORMANCE

Roads and Streets

49. Concrete block pavements provide an aesthetically pleasing road surface that, if properly designed and constructed, is capable of supporting heavy traffic. As pointed out in Part I, European nations have had considerable satisfactory experience with this application of paving blocks. At the U. S. Army Fulda Downs Barracks, Federal Republic of Germany, 70 percent of the pavements have been replaced with paving block over the last 10 years. These pavements performed satisfactorily under truck and M-60 tank traffic. Flexible pavement at one intersection required major patching every 3 to 4 months due to damage from M-60 tanks making 90-deg turns and was therefore replaced with paving block. Inspection of this installation 9 months later found no evidence of damage.*

50. Areas which lack continental Europe's history and experience with small element modular paving have been more hesitant to use concrete block paving in roads and streets. Much of this hesitancy is due to the lack of acceptable design procedures. The U. K. Cement and Concrete Association, the Australian Cement and Concrete Association, U. S. National Concrete Masonry Association, and the U. S. Army Corps of Engineers have issued preliminary or interim design criteria which should encourage further use of concrete paving block in roads and streets (Lilley and Clark 1978, Lilley and Walker 1978, Hodgkinson and Morrish 1980, National Concrete Masonry Association 1980, Department of the Army 1979). Rising prices for bituminous products, low maintenance cost of block pavements, and an increasing emphasis on aesthetic and environmental values may also help to increase use of block pavements in urban and residential roads and streets.

51. Municipalities in the United States have used paving block

* Personal communication, 1978, Mr. D. G. Frandsen, Department of the Army, European Division, Corps of Engineers.

for redevelopment work and also at intersections, bus loading areas, and pedestrian crosswalks. The change in surface texture between conventional and block pavements has been successful in discouraging drivers from encroaching on pedestrian crosswalks. The block pavement roughness limits vehicle speeds to a maximum of 35 to 40 mph and acts as an effective speed control. Some examples of these installations in the United States can be found in Boston, Mass.; Brockton, Mass.; Providence, R. I.; Baltimore, Md.; and El Cerrito, Calif., among others.

52. Approximately 300,000 ft^2 of block pavement in Massachusetts and Rhode Island were examined as part of this project. These pavements were up to 3 years old and were subject to the action of snow plows and deicing salts in the winter and at two locations they were also exposed to salt mist from harbor areas. No environmental or traffic damage was observed. There is one report of freezing and thawing damage to concrete block pavement in Colorado, but no information is available on the quality of block. There is ample evidence in Europe and New England that concrete paving block can be manufactured to withstand abrasion and loads of traffic, deicing salts, and freezing and thawing damage.

53. Block pavements have also been used at railroad crossings. The blocks within the tracks cannot lie immediately adjacent to the rail without striking the railroad car wheel flanges. To solve this problem at a railroad storage yard in England, angle-shaped bars were fixed on the inside web of the rail (Miller-Cook 1980). The vertical leg provided edge restraint for the blocks, and the horizontal leg fixed to the rail provided sufficient offset to allow passage of the railroad car wheel flanges.

Industrial Applications

54. Paving blocks provide an excellent surfacing for a variety of industrial applications and have been used by the Federal Republic of Germany's industry for at least 30 years (Pesch 1980). They are used in a variety of ground level interior or exterior production and storage facilities in heavy industry, power plants, agricultural operations as

well as industrial roads, access roads, courtyards, open areas, ramps, etc. Block pavement will not be suitable for applications which require a clean dust-free floor such as assembly lines for electronic components. Similarly, block pavements are unsuitable in applications such as dairy facilities or meat storage where sanitation and hygiene requirements must be met.

55. Industrial pavements can be subjected to very severe loads from special material handling equipment such as forklifts and straddle carriers, from highly concentrated loads in storage areas, or from impact loading. The magnitude and intensity of this loading often exceed any loadings which occur on nonindustrial roads or streets. Miller-Cook (1980) describes several examples of the severity of these loadings on industrial block pavements. These included a forklift carrying coiled steel plate rolls weighing up to 23.1 tons and a measured load of 9.5 tons exerted on a 3-in.^{2} contact area steel wheel of a trailer. In both of these cases 3.1-in.- (80-mm-) thick block pavements have performed satisfactorily.

56. The Exposaic welded wire manufacturing plant in Mount Airy, N. C., paved an approximate 20-ft width with Z-shaped concrete paving block at the exit of a manufacturing line. Solid tire forklifts pick up completed rolls of wire, exit from the plant onto the paving block, make a 90-deg turn, and proceed to the storage yard or load the wire directly onto tractor trailers. When inspected in 1979, the installation had been in place for approximately 3 years and the manufacturer estimated that a million tons of wire had been carried across the block pavement. The blocks are 80-mm-thick Z-shaped blocks, lying on a 1-1/2-in. leveling course of stone dust with a 5-in. crushed stone base. The blocks show no sign of settlement or chipping. There is some minor surface wear similar to that observed on the portland cement concrete floor inside the plant.

57. Industrial pavements can be subjected to very severe abrasion from solid rubber or steel wheel traffic, short radius turning or scrubbing by heavy vehicles, sliding of loads across the surface, etc. Special paving blocks for very severe conditions have been made with

selected abrasion-resistant aggregate or metal additives. These special blocks have sandblast abrasion resistance as low as 3 cm^3 per 50 cm^2 of surface area compared to the standard paving block's 15 cm^3 per 50 cm^2 (Pesch 1980).

58. Concrete block paving is highly resistant to fuel, hydraulic fluid, oil, or similar materials that may be spilled in an industrial environment. In the United Kingdom a cement-stabilized base is normally used under block pavements in filling stations to reduce the possibility that spilled fuel will seep into the subgrade. To further seal the surface dry sand and cement are also occasionally swept into the block joints. Debris will eventually lower the permeability of the joints, but these precautions provide protection against subgrade and groundwater contamination at the beginning of the pavement life.

59. Concrete paving blocks have also been used in pavements subjected to thermal stresses, and one German plant has stored red hot steel coils directly on a block pavement (Pesch 1980). The blocks are a special composition using blast furnace slag and slag cement.

60. Traffic on block pavements does not have to be delayed for curing, and this offers some advantages when time for pavement repairs is limited. Miller-Cook (1980) describes an application at a London factory where an existing pavement could not be repaired without closing the production line. The old pavement of granite, concrete, and asphalt was removed, and a new block pavement was constructed in 3 days while the plant was closed during a Christmas holiday. Blocks can also serve as a sacrificial layer where severe conditions will cause periodic replacement of the pavements. The modular nature of block pavements will allow damaged portions of the pavement to be easily removed and replaced without grade changes.

61. Future plant expansion, need for future access to control and utility lines, and anticipated settlement are additional situations where industrial block pavements may prove useful. The Berg Steel Pipe Plant in Panama City, Fla., used between 35,000 and 45,000 ft^2 of block pavement for a floor surface inside the plant. Cranes and manufacturing machinery all have reinforced concrete foundations and the remainder of

the interior surfaces are 80-mm-thick Z blocks. The blocks are set on a leveling course of sand over a thick layer of silty sand fill over a soft organic subgrade. Future plant expansion is planned, and portions of the block pavement will have to be taken up and relaid to allow for this expansion and to allow access to buried control systems.

Port Facilities

62. Approximately 17 percent of the total cost of port container terminals goes for pavements (Van Leeuwen 1980). Pavements in both general cargo and container port areas are often subject to heavy concentrated loads; abrasive traffic; and spillage of various lubricants, fuels, and hydraulic fluids. In addition port facilities are often built on fill areas subject to large settlements, and block pavements are economical under these conditions.

63. The largest single application of block pavement has been at Port Rashid in the United Arab Emirates where over 4 million ft^2 of 100-mm-thick block were placed in less than a year (Precast Concrete 1979). The United Kingdom first used concrete block pavement for a port facility in 1975 at Cardiff for a 6450-ft^2 loading bay, and as shown in Figure 18 (constructed from data reported by Gerrard (1980)) use of block paving in U. K. ports grew rapidly in the next 5 years. All of the United Kingdom pavement reported by Gerrard (1980) used 80-mm-thick blocks.

64. The Europe Container Terminus in Rotterdam has installed 11.8 million ft^2 of block pavement since 1967. The pavement consists of 120-mm-thick blocks, 2 in. of crushed rock or gravel, and 4.7 in. of cement-stabilized sand over sand fill (Van Leeuwen 1980). The anticipated settlement was 3.3 to 4.9 ft during the first 10 years. Examples of some of the loadings include 11-ton axle loads which are expected to soon rise to 13.2 tons, straddle carriers with wheel loads of 16.5 tons, and 33- to 44-ton stacked container loads transferred to the pavement through four corner supports each with a 2.3-in. contact area. Under these conditions block pavements have provided a highly satisfactory

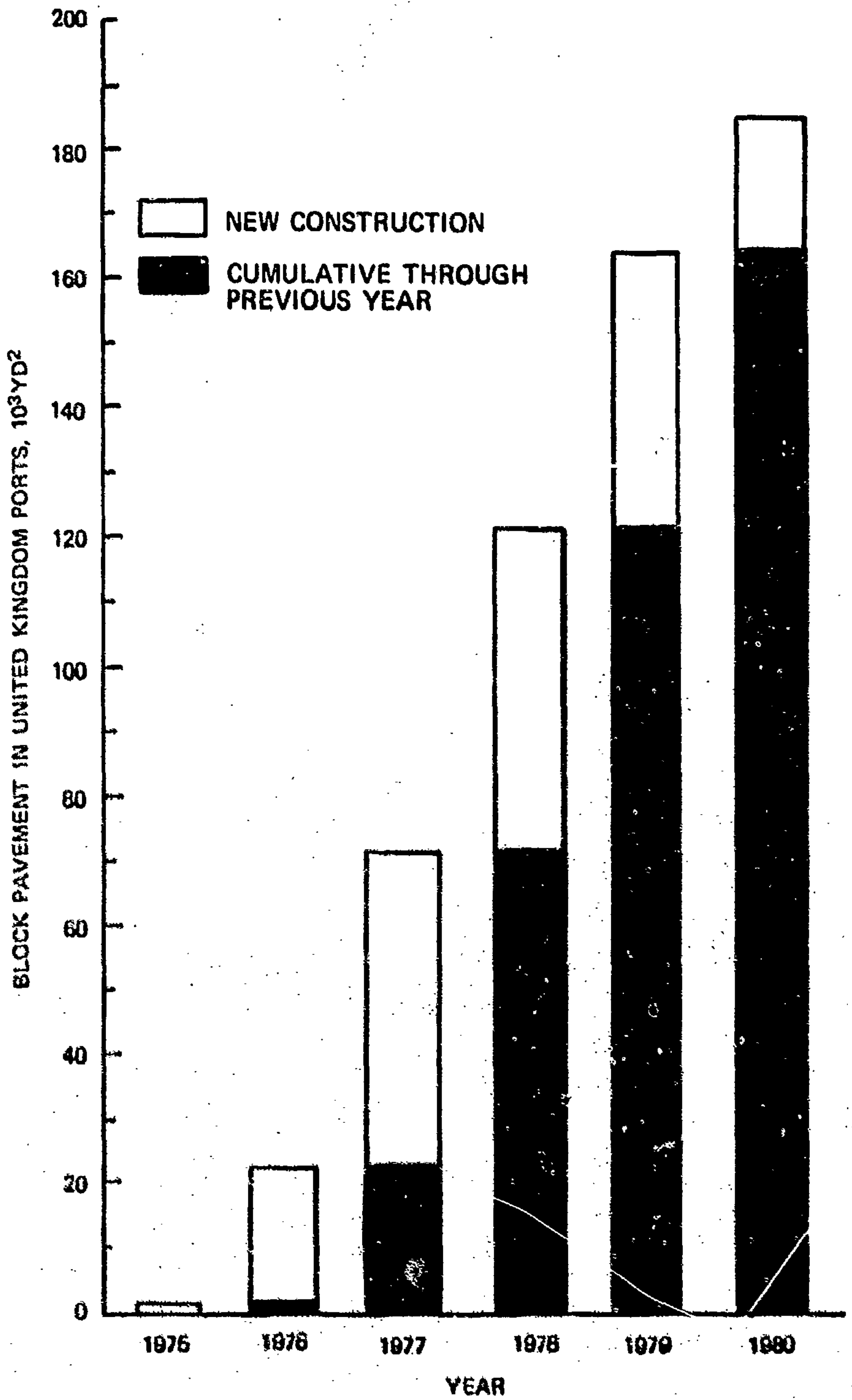


Figure 18. Use of paving block in U. K. ports

surface for 13 years in a port facility handling 850,000 containers a year (Van Leeuwen 1980).

65. Pavements in port facilities face severe loading conditions, and block pavements have proven satisfactory for this application. Patterson (1976) reviewed pavement requirements for container terminals and recommended surfacings shown in Table 4 for varying load and settlement conditions. The surfacings considered were asphalt, tar, cast in situ concrete, precast concrete slabs, concrete blocks, and staged construction. Local economic conditions may cause some variations in the order in each category, and block pavements were generally most suitable when settlement was anticipated.

Drainage

66. The numerous sand-filled joints between individual blocks in the pavement can allow water to soak into the underlying base, subbase, and subgrade. This can result in a reduction in strength of the supporting layers and unsatisfactory pavement performance. Weakening of a clay subgrade by infiltration of surface water is one suggested reason for the premature failure of a test item in an experimental installation of a block pavement in the U. K. (Barber and Knapton 1980), and a subbase weakened by infiltrating moisture from a heavy rainstorm is blamed for the 1976 failure of a block pavement in a port area (Gerrard 1980).

67. It is widely accepted but unproven that the block surface becomes impermeable under traffic as rubber, oil, and other debris accumulate in the joints. Often a new block pavement is assumed to have 10 percent initial permeability to surface water which is claimed to decrease to near zero with time (National Concrete Masonry Association 1979, Cruickshank 1976). In both of the previously mentioned failures, the rains occurred while the block pavement was new and the joints relatively free draining. Nevertheless, it appears to be unrealistically optimistic to expect a block pavement to become impermeable. For instance, Barber and Knapton (1980) report from field observations in Europe that water ponding on the surface of a block pavement will

percolate through the joint and into the pavement structure.

68. Surface infiltration is a recognized source of water in conventional pavement structures. The Federal Highway Administration (1980) recommends multiplying the design precipitation rate by coefficients of 0.50 to 0.67 for portland cement concrete pavements and coefficients of 0.33 to 0.50 for asphaltic concrete pavements to determine the design water infiltration rate through these pavement surfaces. Gerrard (1980), based on his experience with the previously mentioned port failure, recommends that suggested infiltration rates of 10 percent for block pavements be increased; and Lilley (1980), based on work by Clark (1979), recommends not using moisture-sensitive material in the base of the block pavement. Erosion and pumping of sand from the laying course into shrinkage cracks of a cement-stabilized base are blamed for settlements in an experimental block road in Denmark (Lesko 1980). Surface infiltration is obviously a problem in block pavements and the assumption that they become impermeable with traffic is not justified. There have been suggestions to use bituminous seal coats or waterproof membranes on base or subgrade layers and to seal the surface by sweeping dry cement or dry clay into the joints, but no field applications of these techniques are known.

69. Block pavements initially allow a high rate of water infiltration. This decreases with time under traffic and perhaps becomes similar to a conventional pavement surface. Periodic measurements of surface permeability of a test pavement in Australia are planned and may provide more insight into this important problem (Sharp 1980). To reduce the effect of moisture, the Corps of Engineers limits the plasticity index of base and subbase material in flexible pavements to 5 or less (Department of Defense 1978). Also all design strengths of the subgrade, subbase, and base are selected from soaked California Bearing Ratio (CBR) tests to allow for strength loss due to moisture. Although base and subbase material in pavements have generally been considered free draining, current information suggests that these materials actually have low permeability and are saturated for long periods of time (Nettles and Calhoun 1967, Cedergren 1974, Federal Highway

Administration 1980). Block pavements have essentially the same problems with moisture as conventional pavements and will require the same surface and subsurface drainage considerations. Selection of material properties to limit moisture effects and evaluation of soil strengths on the basis of soaked test samples appear necessary.

Cost and Maintenance

70. Cost of paving blocks varies considerably due to local differences in labor, material, block quality and size, and transportation costs. According to interviews with several U. S. manufacturers in 1979, 80-mm- (3.1-in.-) thick block cost about \$0.90 to \$1.00 per ft^2 at the manufacturing plant and could be laid for \$0.50 to \$0.65 per ft^2. These rates are similar to 1978 rates of \$0.86 per ft^2 and \$0.38 per ft^2 quoted by Harris (1978) for 76-mm- (3.0-in.-) thick blocks in Perth, Australia. Transportation costs have to be added to these figures. Table 5 compares the price for paving block in place from several different sources. The currency exchange rates in Table 6 were used for all conversions. Direct comparison of these prices is also hindered by inflation during this period and by other factors such as project size, transportation costs, and the extent of acceptance of block paving in the local construction market.

71. When paving blocks are first introduced into a new market area, initial construction costs are likely to be high due to contractors' unfamiliarity with paving blocks. In extreme cases contractors may decline to bid on paving block, and in a few cases manufacturers have had to lay their product themselves in a new market area. As the product becomes familiar to construction contractors, bids become more competitive. Table 7 is developed from data reported by Gerrard (1980) and compares bid prices from six contractors for a large block paving job at Dover, U. K. The coefficient of variation of the bids for the block laying is half that of the bids for construction of the conventional lean concrete base, indicating acceptance and competitiveness of the block pavements in that local construction market.

72. Table 8 compares the reported initial construction costs for several types of pavements. The block pavements are competitive in the U. K. and Netherlands application, but are three to five times more expensive in the Australian application. This may be due to a variety of factors such as different design loads, the changing relative price of petroleum-based products from 1978 to 1980, the possible requirement to design for settlement in port areas, or competitiveness of a well-established paving block industry in Europe. In the U. S., block pavements are generally more expensive than conventional paving material, but are often less expensive than decorative paving such as brick.

73. One advantage claimed for block pavements is reduced maintenance. In 1969 the German firm Bauberaturg Zement Hannover conducted a study of 87 block roads constructed between 1957 and 1969 to determine maintenance costs and traffic damage to block pavements.* The traffic damage results are shown in Table 9. Initial costs of block pavements exceeded asphalt pavement by 4 to 14 percent, but after 10 years when the asphalt was overlaid, the block pavement had lower total costs.

74. Other reports support these suggestions of low maintenance costs. The block pavements at the heavily loaded and settlement-prone container terminal at Rotterdam required maintenance one time in 10 years at a cost of \$0.74 per ft^2, which was twice the reported maintenance interval and two-thirds the cost of maintenance for asphalt and concrete (Van Leeuwen 1980). Experience in the Netherlands with block paving in urban areas suggests that the blocks have a lifetime of 40 years and that once during this lifetime a full-scale repair will be needed which will reuse 90 to 95 percent of the original paving blocks (Kellersmann 1980). Estimates of maintenance requirements should be based on local experience, but there is often insufficient information available in areas such as the U. S. where paving blocks are relatively new.

75. Sharp (1980) estimated costs in Australia for a 40-year life

* Manufacturer's sales literature describing this study translated and provided by European Division, U. S. Army Corps of Engineers. Now on file at Office, Chief of Engineers (DAEN-MPE-D), Washington, D. C.

of asphalt, sprayed seal, and interlocking block pavements. A total of 36 pavements were analyzed with subgrade CBR's of 3, 8, and 20, and traffic levels ranging from 10^3 to 10^7 passes of an equivalent 18-kip single-axle load. These traffic levels are relatively low and are representative of residential or minor urban streets.

76. The data from Sharp (1980) was used to prepare Figure 19,

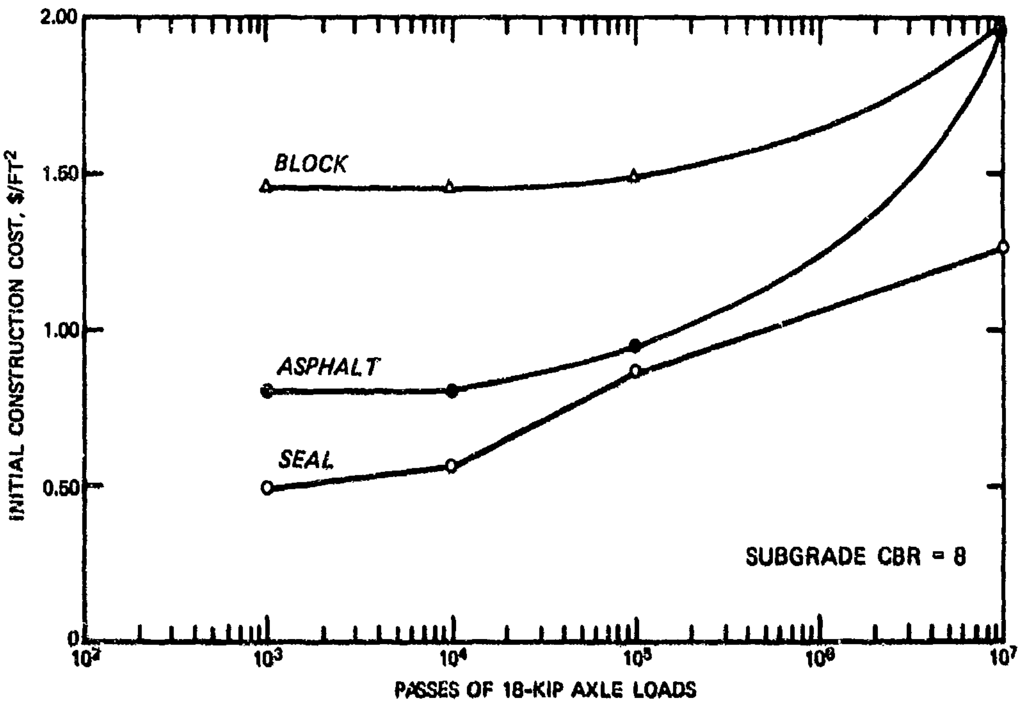


Figure 19. Comparison of initial pavement costs

which compares the initial construction costs of the three types of pavement for varying traffic levels. Only at the higher levels of traffic considered by Sharp does the block pavement become competitive with asphalt, and the sprayed seal always retains a cost advantage. In Figure 20, the initial construction and maintenance costs have been converted to a single 40-year future worth, assuming an 8 percent interest rate (Sharp 1980). No maintenance costs were included by Sharp (1980) for the block pavements, so a 20-year reconstruction of the block pavement was assumed, as suggested by Kellersmann (1980). The cost of this

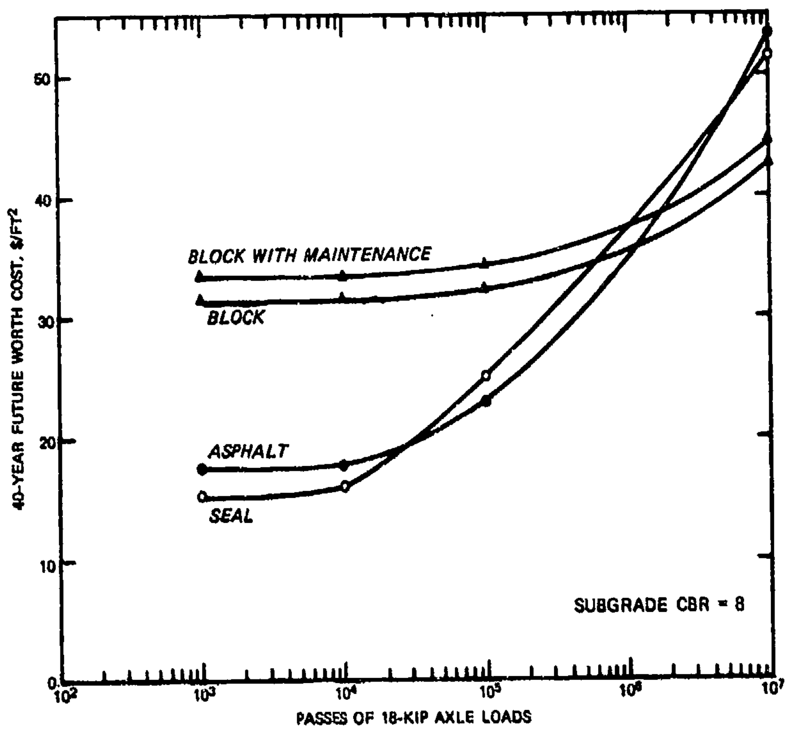


Figure 20. Comparison of 40-year future worth pavement costs

reconstruction was estimated assuming a 5 percent block replacement and using the laying and block costs developed by Harris (1978) and described earlier in this Part. This was added to the 40-year future worth using Sharp's assumption of an 8 percent interest rate over the remaining 20 years. When maintenance costs are included in the analysis, the relative costs of the pavements change with different traffic levels with each one becoming the most cost-effective at some point. Although this analysis cannot be translated directly to other areas, it illustrates the effect of several parameters in evaluating the cost of block pavements. Maintenance costs must be included in all evaluations that attempt to judge relative cost-effectiveness of different types of pavements.

Surface Properties

77. Block pavements are not as smooth as conventional pavements,

and maximum vehicle speeds are limited to approximately 30 to 40 mph (Lilley and Walker 1978). Table 10 compares minimum Army pavement smoothness requirements with the maximum allowable surface deviation for block pavements from two European sources. Block pavements meeting the suggested European smoothness requirements will not meet Army pavement requirements. For this reason the Corps of Engineers limits precast concrete paving blocks to low-speed pavements, storage areas, and walkways (Department of the Army 1979).

78. Skid resistance has not been a problem with block pavements. The only known exception to this statement are two car parks in England described by Lilley (1980). These car parks were constructed with blocks that contained a large proportion of calcium carbonate in the fine aggregate, and these blocks polished under traffic within a few weeks, providing a pavement surface with unsatisfactory skid resistance. U. K. Cement and Concrete Association and Interpave Specifications for concrete block adopted a 25 percent limit of acid-soluble material in the fine aggregate for paving block to avoid further problems of this type. Kellersman (1980) reports that although many brick pavements have become polished and slippery under traffic, no concrete block pavement has been replaced for skid resistance in Amsterdam during the 20 years that concrete blocks have been in use.

79. Tests of skid resistance of concrete block have generally found that they provide acceptable levels of skid resistance. Harris (1978) reports that tests with the Transport Road Research Laboratory portable skid resistance tester on paving block indicated very good low-speed skid resistance. Tests with the California portable skid tester on untrafficked paving blocks measured friction factors of 0.46 to 0.47 compared to a minimum requirement of 0.30.* Figure 21, developed from data reported by Meyer (1980) and Lesko (1980), shows that skid resistance of paving block descreases sharply under initial traffic, but this effect lessens after the first year. Figure 22 is developed from data

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* Personal communication, Mr. Dan Williams, Muller Supply Company, Lodi, Calif.

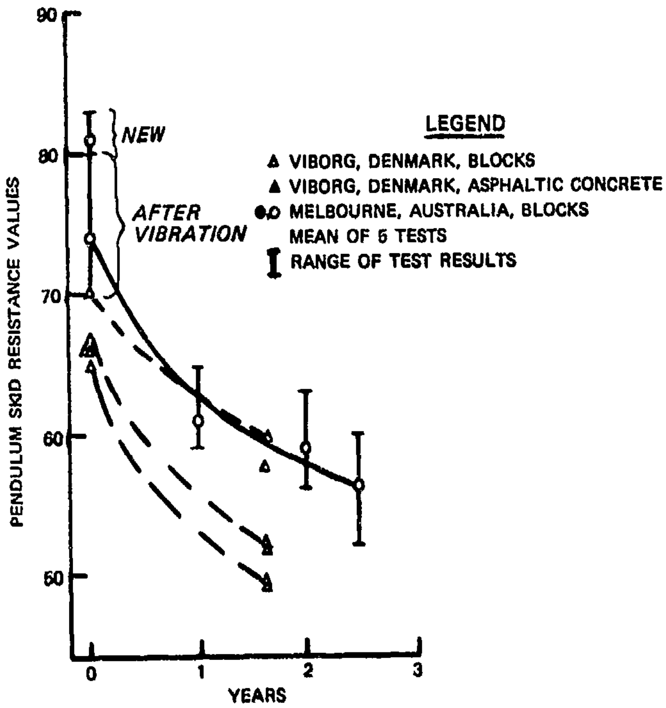


Figure 21. Loss of skid resistance with pavement age

reported by Lesko (1980) that shows that the paving block skid resistance decreases with age and increases in speed. Although the block skid resistance is lower than for asphaltic concrete, it is above the established Danish minimum requirement.

80. The skid resistance of a paving block surface is affected by a large number of factors, such as tire characteristics, vehicle speed, surface moisture conditions, block surface texture, and quality of the fine aggregate used in manufacturing the paving block. Experience to date indicates that paving block pavements will provide an adequate skid-resistant surface for low-speed traffic provided that the blocks are manufactured with polish-resistant fine aggregate and have a textured surface.

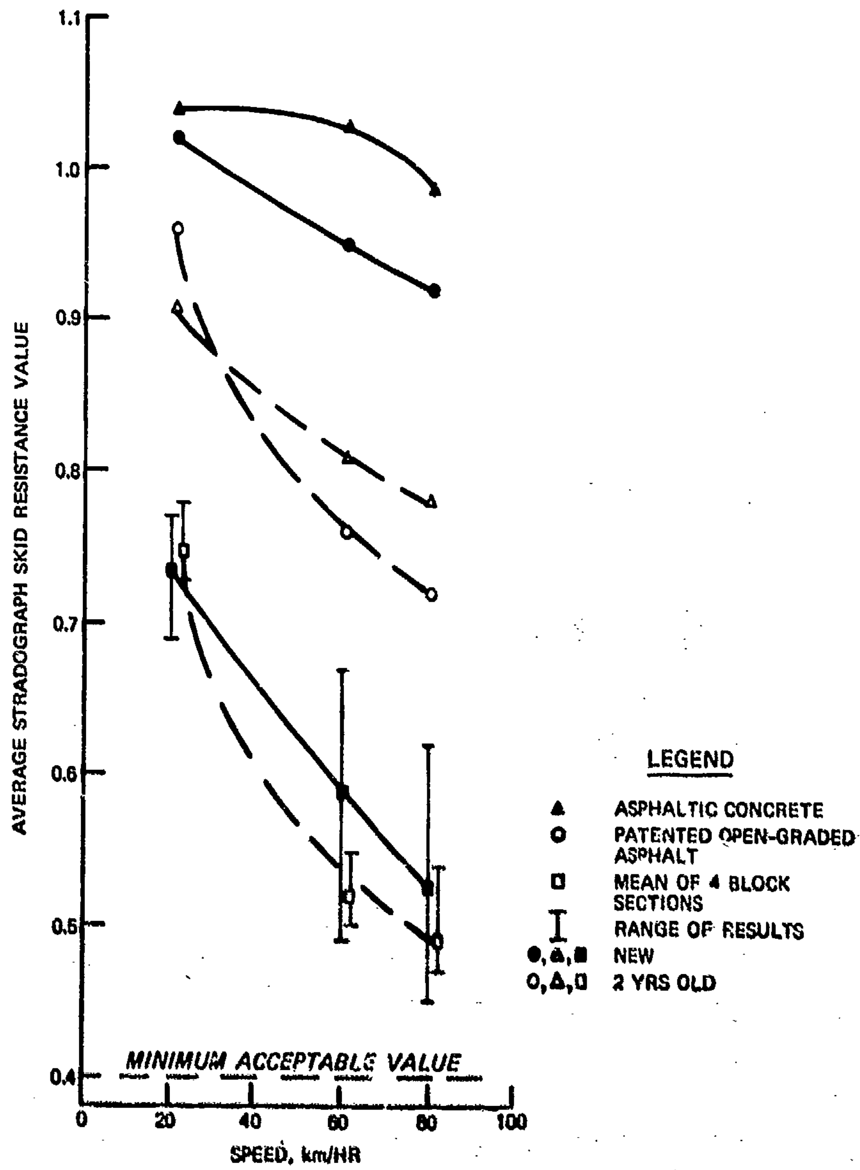


Figure 22. Effect of speed and age on skid resistance at Viborg, Denmark

PART V: BLOCK PAVEMENT TESTS

81. Continental Europe's long history of using brick, cobblestone, etc., in modular paving construction allowed an easy adoption of concrete paving block. The traditional design and construction procedures were easily modified for use with their new products, and there was no need for testing to evaluate the performance of block pavements. When the paving block industry spread to other areas without continental Europe's background, questions arose concerning the design and performance of block pavements. This led to a series of tests by different organizations to evaluate the performance of block pavement and to collect data on design for these pavements.

United Kingdom Tests

Laboratory plate load tests

82. The U. K. Cement and Concrete Association conducted plate load tests of six different block shapes ranging from 2.4-in.- (60-mm-) to 3.9-in.- (100-mm-) thick to determine the load-carrying characteristics of block pavements. These tests are described in detail by Knapton (1976) and Clark (1978). A 6- by 6-ft area was paved with paving blocks. The blocks were on a 2-in.-thick sand leveling course, and lateral restraint for the blocks was provided by timber curbs. Normal construction methods were used to place and vibrate the blocks. The bases used under the sand course were concrete, crushed stone, and dense polystyrene.

83. Loads were applied to the block surface by a hydraulic jack and a 9.8-in.-diam circular steel plate. An array of pressure cells located flush with the base surface and directly under the sand layer measured the distribution of the load through the paving block and sand layers. Figure 23 shows that the paving block does distribute loads, and pressures measured on the base are significantly reduced. Figure 24 shows that the shape of the block had no influence on the load distribution of the block surface. Also, the thickness of the block had a relatively modest effect on the load-distributing characteristics of the block pavements.

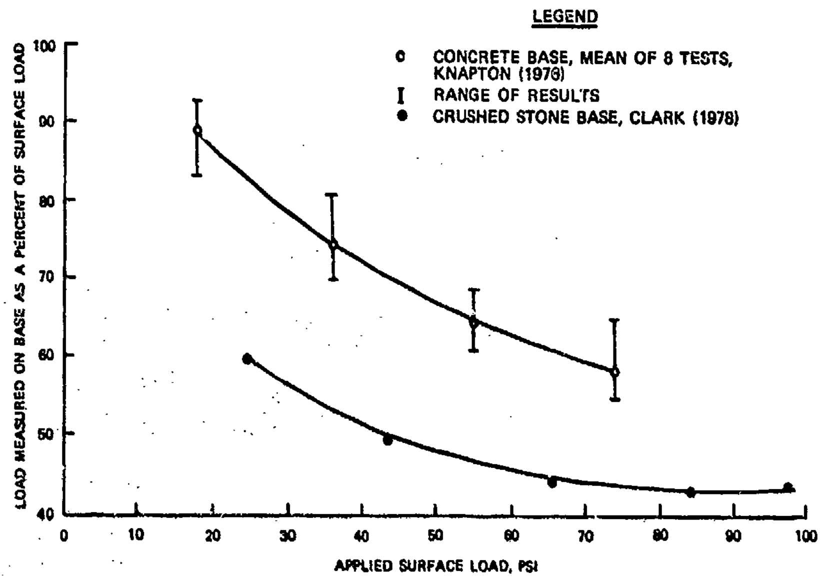


Figure 23. Applied loads on the pavement base under block surfaces

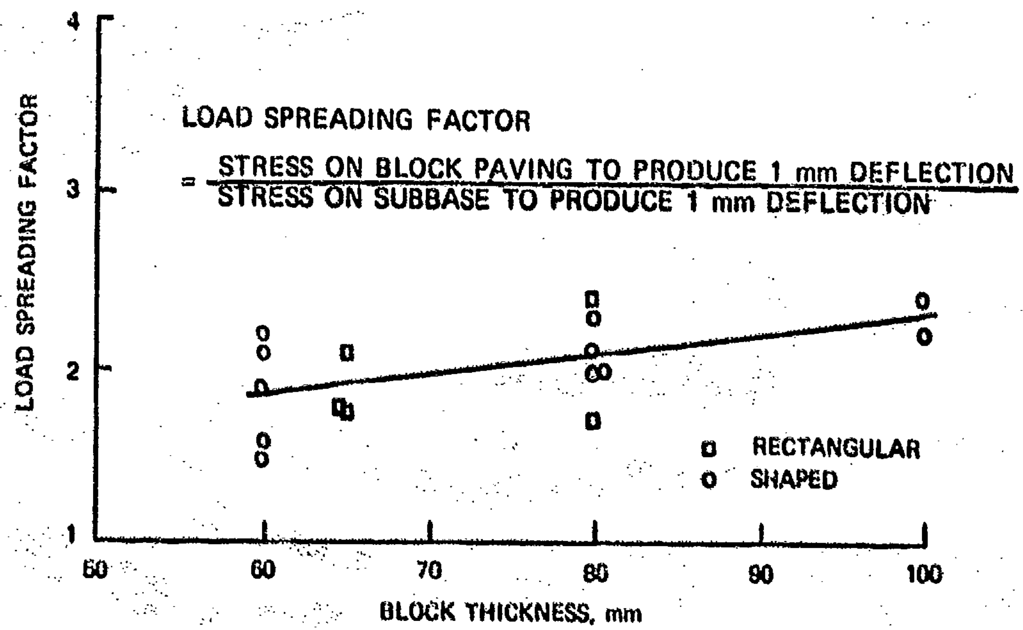


Figure 24. Effects of block thickness and shape (Clark 1978)

84. These tests demonstrated that the blocks develop side friction, rotational resistance, interlock, or some combination of these factors to distribute vertical loads. Knapton (1976) used these results to develop an approximate design method by replacing the paving block and sand layer with an equivalent 6.3-in. (160-mm) layer of flexible pavement structure.

Field plate load tests

85. Knapton and Barber (1979) described a series of field plate load tests on a paving block surface. The subgrade was an inorganic clay of medium plasticity with a CBR of 2 percent. A granular limestone base varied from 2 to 15.7 in. thick. Rectangular concrete blocks, 7.9 by 3.9 by 3.1 in., were laid in a herringbone pattern on 2 in. of loose bedding sand. The blocks were vibrated into the bedding layer with 2 to 3 passes of a small vibratory plate compactor. Dry sand was then swept over the block surface, and the blocks were revibrated. Precast concrete edge channels set in lean concrete provided edge restraint for the pavement test section. The final size of the block surfaced test section was 10.0 by 19.7 ft.

86. The test section was repetitively loaded with 14,100 lb on a 7.9-in. square plate, and permanent surface deformations for varying numbers of load repetitions were recorded. Each loading was considered to be equivalent to 30 applications of a standard 18-kip axle load. The load was applied at seven locations where the granular base was 2.0, 5.9, 7.9, 9.8, 11.8, 13.8, and 15.7 in. thick.

87. When the load was applied to the section with a 2-in. base, failure occurred immediately. Three blocks split in half, and the loading plate punched the surface outlined by the faces of the broken blocks and block joints into the subgrade. Figure 25 shows the cumulative vertical deformation measured on the other base thicknesses at various numbers of load repetitions.

88. This test demonstrated that if an adequate base is used, a block pavement could support heavy loads on a soft clay subgrade. Observations during this test revealed that initial settlements occur until the blocks achieve interlock and thereafter further deformation, y ,

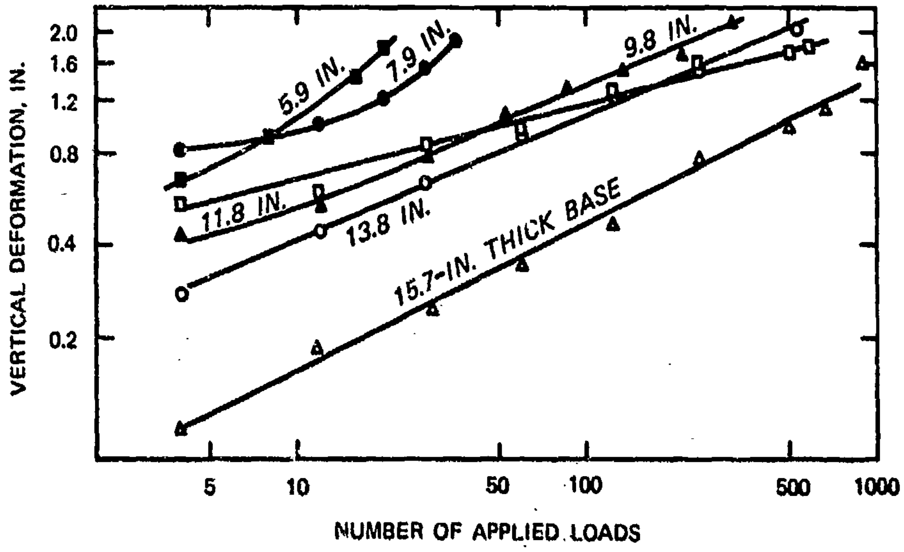


Figure 25. Effect of base thickness and load repetition on vertical deformation (Knapton and Barber 1979)

depends on the number of load repetitions, N , described by the form, $y \propto N^n$. For these tests n averaged 0.37.

<u>Water penetration tests</u>

89. Clark (1979) investigated the amount of water that penetrated a newly placed block surface. A block surfaced test section was constructed in a 6.6- by 6.6-ft concrete tank, as shown in Figure 26. Water was applied to the block surface at different rates, and the amounts of water that collected in the drainage channel and that penetrated the block surface and exited from the drainage outlet were measured. The

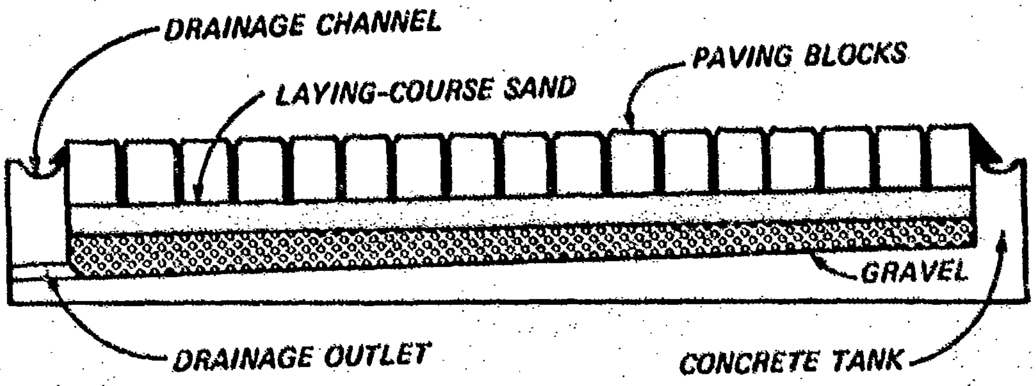


Figure 26. Water penetration test bed (Clark 1979)

water was applied to the surface until the outflow from the drainage outlet reached a constant rate for a period of 20 min. Each test generally took 45 to 60 min.

90. Table 11 summarizes the results of these tests. The mean penetration of water through the block pavements with a slope of 1 percent and clean sand in the joint was 19.6 percent with a coefficient of variation of 14.7 percent. The limited range of block surface slopes used in this test did not show any definite effect due to slope. Clark (1979) postulates that the difference in water penetration between tests 1 and 2 was due to accumulation of dust and fine particles in the joints during the 28-day interval between tests. However, because of the inherent variability of the test results, more data are needed to verify this suggestion. An addition of clay dust to the joint filler sand in tests 8 and 9 reduced the water penetration to a mean of 11.5 percent. Clark (1979) suggests that the sharp drop in water penetration in test 10 was due to the clay particles swelling during the 24-hr delay between tests 9 and 10. Before Test 11 fine top soil was brushed onto the surface of the joints rather than mixing with the sand joint filler to try to simulate the sealing of the joints with debris under traffic. This reduced the quantity of inflow measured at the drainage outlet for about 50 min, but then flow increased until the penetration rate in Table 11 was reached at a steady-flow rate.

91. This series of tests clearly shows that large water penetration is possible in newly constructed block pavements. The tests do not provide any information on permeability of in-place pavements which have been subjected to traffic. This leaves the belief that block pavements become impermeable due to accumulation of oil, rubber, and debris under traffic without experimental verification.

Industrial road test

92. Barber and Knapton (1980) described an experimental installation of a paving block pavement at the exit of an industrial yard. The test section was approximately 6.6 by 65.6 ft in area and situated so that the wheels on one side of each entering or exiting vehicle had to travel the length of the block pavement test section. This test section

was traversed by 57.3-kip four-axle articulated trucks, 41.9-kip three-axle rigid trucks, and 33.1-kip two-axle trucks. The equivalent 18-kip axle loads for each pass of these vehicles is 3, 1.4, and 1.6, respectively (Barber and Knapton 1980).

93. The test section was constructed by breaking out a portion of an existing concrete pavement. This existing concrete pavement provided edge restraint on all sides for the block pavement test section. Ten test items, each approximately 6.6 by 6.6 ft in area, were constructed with varying base thicknesses and block shapes as shown in Table 12. A natural sandy clay was the subgrade for 6 items, a different sandy clay was placed as backfill for the subgrade in 3 items, and heavy clay was encountered in one item. Properties of these soils are shown in Table 13. The water table was less than 11.8 in. from the subgrade surface.

94. An unwashed and unprocessed local sand was used for the base for all test items. The gradation of this material (Figure 27) shows it is a poorly graded fine sand. Also shown in the figure is the gradation usually required for a base material in the United Kingdom.

95. Two types of blocks were used to surface the test items. Items 1-5 used a 3.9- by 7.9-in. rectangular block, and items 6-10 used a 4.4- by 8.8-in. shaped proprietary block. All blocks were 3.1 in.

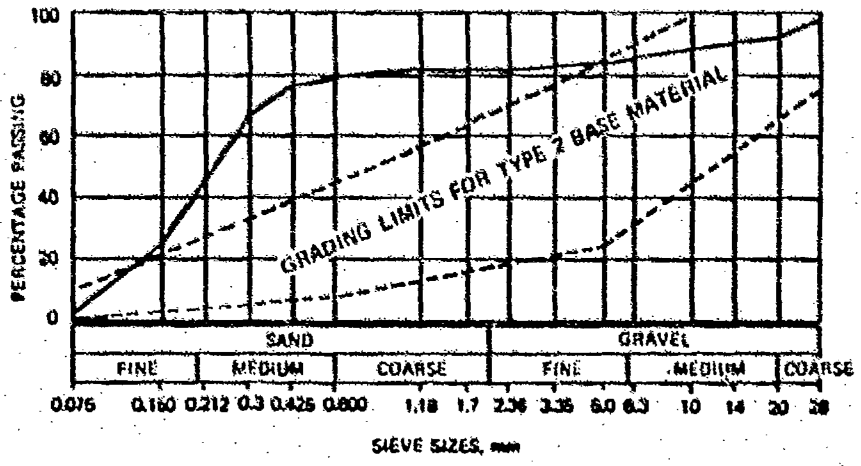


Figure 27. Industrial road base course gradation (Barber and Knapton 1980)

thick and laid in a herringbone pattern. Construction of the block pavement test section followed normal procedures. A 2- to 2.4-in.-thick uncompacted sand leveling course was placed; the blocks were laid on this, and then vibrated with additional sand vibrated into the joints from the surface.

96. Deformations of the surface under traffic were measured periodically to an accuracy of ±0.02 in. with an accurately leveled straightedge and a vernier caliper. Table 14 shows the maximum measured deformation at various traffic levels. High initial settlements were recorded in the first 300 axles of traffic with smaller deformations recorded thereafter. Barber and Knapton suggest that the large deformation in items 9 and 10 was due to inadequate compaction of the sandy clay backfill and heavy rains which fell shortly after the test section was opened to traffic.

97. Three different types of surface profiles, as shown in Figure 28, developed under traffic. Item 1 had a general overall settlement, indicating densification of the base under traffic, but probably little or no shearing in the base or subgrade. Item 10 showed a sharp unheaval of 1 in. above the untrafficked profile, indicating that the base or subgrade was shearing. Item 8 had a similar profile with an upheaval of almost 0.5 in. above the original surface. The remaining items had profiles similar to item 5 in Figure 28 with two distinct ruts but no upheaval above the original surface. It is uncertain whether this shape is due to densification in two narrowly trafficked lanes, shear movement, or a combination of these effects.

98. Some of the conclusions reached by Barber and Knapton (1980) from this test are:

a. Inferior quality granular bases can be used with block pavements on low-strength clay subgrades for light residential traffic.

b. The deformation of a block pavement is characterized by high initial settlements, followed by much smaller progressive deformations which are approximately linear on a logarithmic time scale.

c. Improved compaction could lower the high initial settlements in the substandard granular base.

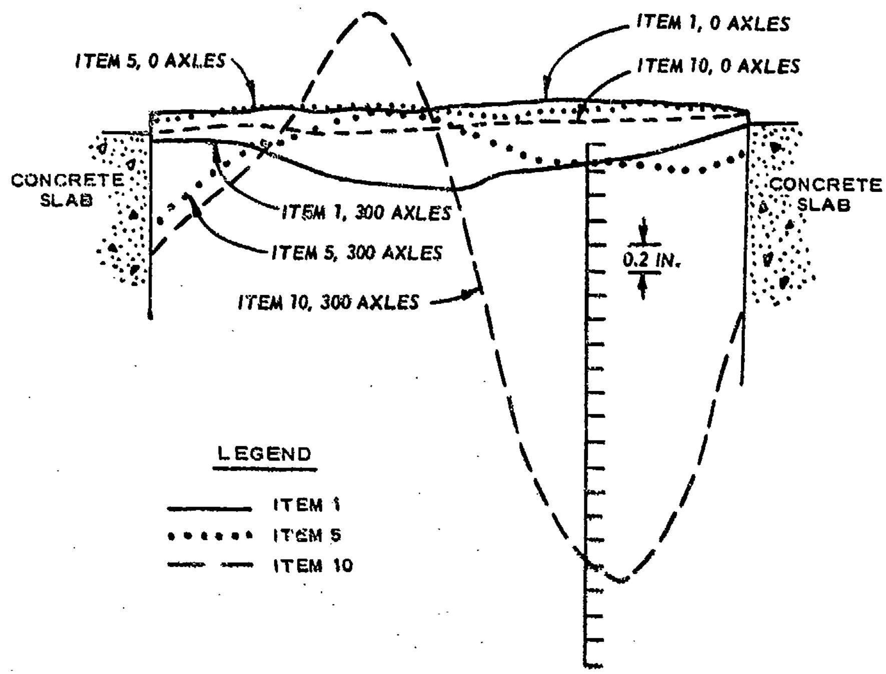


Figure 28. Surface profile from industrial road

d. A significant proportion of the initial settlement is due to compaction of the sand laying course.

e. The block pavement is not watertight. The base should retain its strength when wet, and the subgrade should be protected by a waterproof membrane if it will lose strength at high moisture contents.

New Zealand Tests, Canterbury Circular Test Track

99. Seddon (1980) describes the traffic tests of two block test sections at the Canterbury circular test track. The Canterbury circular test track moves an 8990-lb load on twin truck tires around a circular test track that has a mean diameter of 30.2 ft. Traffic is applied at a velocity of 25.7 mph and is distributed over a 4.1-ft-wide traffic lane. The natural subgrade at the test track is a greywacke gravel deposited by the Waimakeriri River. An artificially weak test subgrade is formed by placing 0.47 in. of tire rubber between two filter fabrics on top of the natural subgrade. This tire rubber consists of dusty flakes with a consistency similar to pipe tobacco. This artificial subgrade

gives high deflections with artificially steep deflection basins.

100. During a test of nine different base course materials at the test track, one base course failed after 150,000 wheel passes and had to be replaced. The base course test sections were each 9.8 by 21 ft and consisted of 5.9 in. of a granular subbase over the rubber subgrade, followed by a filter fabric, 5.9 in. of base material, and a chip seal surface. The failed base material was removed, and 2.4 in. of sand for a laying course was placed on the subbase. Blocks 3.1 in. thick were laid in a herringbone pattern. Two different interlocking shaped blocks were used and were identified as "Pavelock" and "Unipave."

101. One hundred thousand passes were applied on the test track. Figures 29 to 31 show the surface deformations recorded during these tests. Resilient deflections decreased with increasing traffic. Rut depth had high initial values and then increased more slowly with traffic, and the transverse profile showed significant shear upheaval outside the traffic lane. The increase of density of the sand layer under traffic is tabulated below:

	Density, lb/ft^3		
Block	Center line of Traffic	Outer Area of Traffic Lane	Untrafficked Area
Pavelock	116.6	115.6	106.9
Unipave	114.6	117.4	104.7

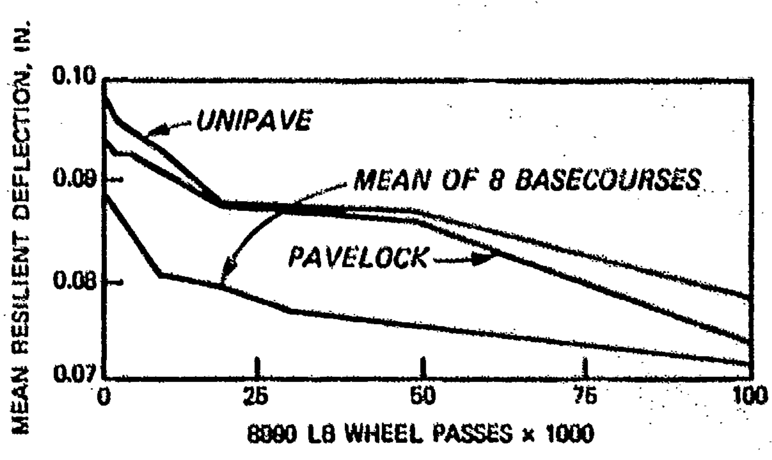


Figure 29. Benkelman beam deflections in concrete block and unbound granular base course pavements (Seddon 1980)

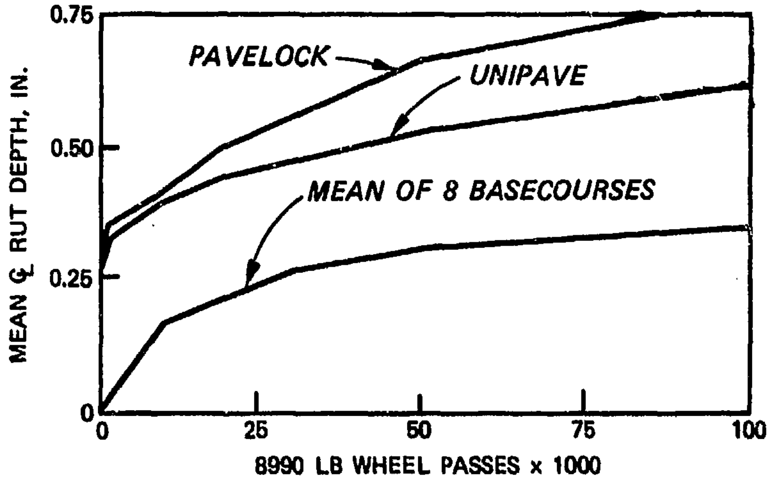


Figure 30. Mean center line rut depths for concrete block and unbound granular base course pavements (Seddon 1980)

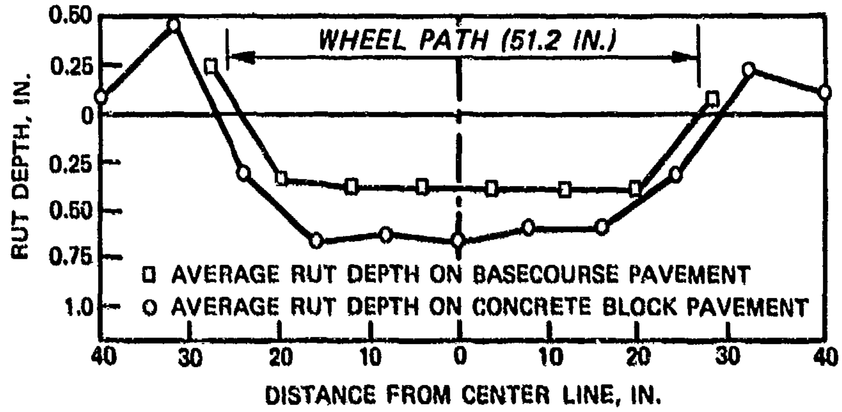


Figure 31. Transverse profiles of rut depth at 100,000 wheel passes (Seddon 1980)

Laboratory compaction tests (New Zealand Standard DZ 4402, 1979) found that the sand had a dry density of 118.0 lb/ft^3 when compacted at zero percent moisture. This dropped off to a minimum of 108.0 lb/ft^3 at 4 to 5 percent moisture and then rose to 113.6 lb/ft^3 when compacted at a 13 percent moisture content. The untrafficked densities in the tabulation above suggest that the sand was at about 90 percent of the laboratory density after the block pavement surface was seated with the vibratory plate compactor. Under traffic this density increased to over

98 percent of the laboratory density.

102. The Pavelock blocks had a compressive strength of 5,420 psi, while the Unipave had a compressive strength of 8,210 psi. No blocks showed any distress after 100,000 wheel passes.

103. An analysis with an elastic layer computer program was able to match measured and computed deflection basins of the block pavement by representing the blocks as an elastic layer of material with a modulus of elasticity of 60,200 psi and a Poisson's ratio of 0.25. However, the elastic layer analysis is not considered adequate by Seddon (1980), and further analytical work is planned using a finite element program.

104. Some of Seddon's (1980) conclusions drawn from this study are:

a. Concrete block pavements behave in a manner similar to flexible pavements with a thick surfacing.

b. On the basis of deflection basins concrete block pavements showed no greater stiffness than the chip seal surfaced base course test items.

c. Excessive permanent rutting and possibly large initial transient deflections were due to the sand layer.

d. The rounded beach sand used in the laying course was not suitable for the loads used.

e. Improved methods of seating the block surface and compacting the loose sand laying course need to be studied.

Australian Tests

Road simulator tests

105. Shackel (1978) and Shackel and Arora (1978a) described a series of tests on block pavements with the University of New South Wales Road Simulator. The road simulator is a concrete trough which allows construction of pavements 13.8 ft wide and 4.9 ft deep. A pavement length of 14.8 ft is available for testing. Simulated traffic loads are applied by hydraulic jacks to a series of seven 7.9- by 7.9-in. steel plates to represent a load moving at 0.5 mph.

106. Block and base thicknesses and loads examined in this test are tabulated on the next page. Figure 32 shows a typical cross section

Block Thickness	Base Course Thickness 2.4 in.	3.9 in.	6.3 in.
3.9 in.	X	X	X
	0	0	0
3.1 in.	X	X	X
	0	0	0
2.4 in.	X	X	X

NOTE: X - 87 psi, 0 - 131 psi.

of the test section. A sandy loam subgrade was left in the concrete trough from previous pavement tests, and additional sandy loam subgrade material was obtained from the original source in Emu Plains, New South Wales to backfill the existing test section to the new test levels. However, as shown in Figure 33, the new sandy loam backfill gradation differed from the original sandy loam subgrade slightly. Shackel and Arora (1978b) reported that the original sandy loam was nonplastic, had a specific gravity of 2.64, had a modified American Association of State Highway and Transportation Officials (AASHTO) optimum moisture content of 8.5 percent, and had a modified AASHTO optimum density of 125.9 lb/ft^3. The new sandy loam backfill was reported to have similar characteristics but somewhat lower compaction test results (Shackel and Arora 1978a). Shackel (1979) reports the subgrade CBR as 65 percent. Shackel and Arora (1978a) reported that the dolerite base material did not differ significantly from the dolerite base used previously by Shackel and Arora (1978b). This material was described as nonplastic, with a specific gravity of 2.87, modified AASHTO optimum moisture content of 6.5 percent, and a modified AASHTO optimum density of 149.2 lb/ft^3. The gradation of the dolerite base is shown in Figure 33. All blocks were identical interlocking shapes laid in a herringbone pattern.

107. Data on permanent vertical deformation, horizontal movements, resilient deflections, and pressure cell readings were collected after 1,000 and 13,000 passes of the test loads. A typical transverse rut profile is shown in Figure 34. Regression equations were developed for each loading pressure to individually relate permanent vertical deformations, resilient deflections, and stress distribution to block and base

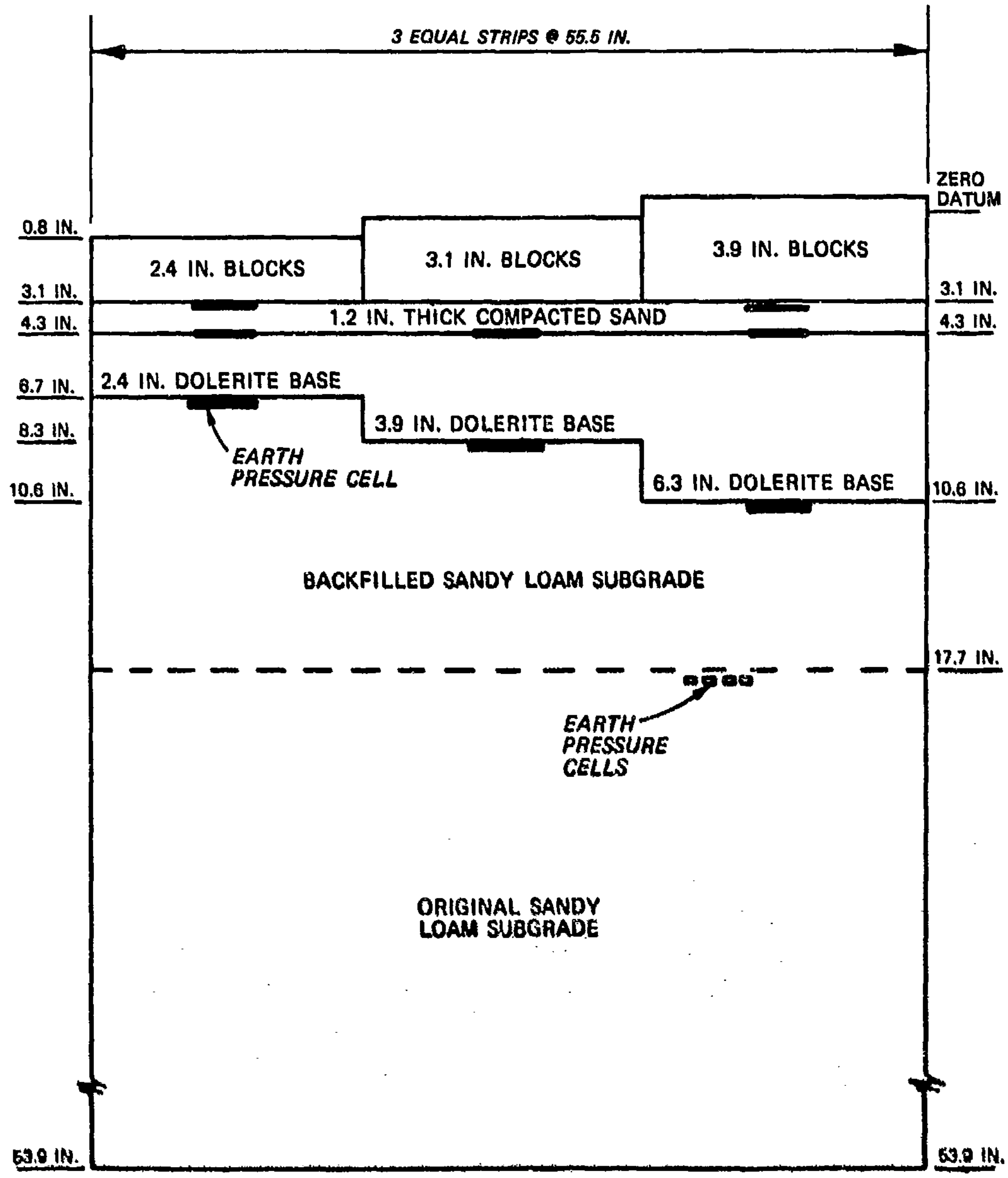


Figure 32. Typical cross section of road simulator block test section

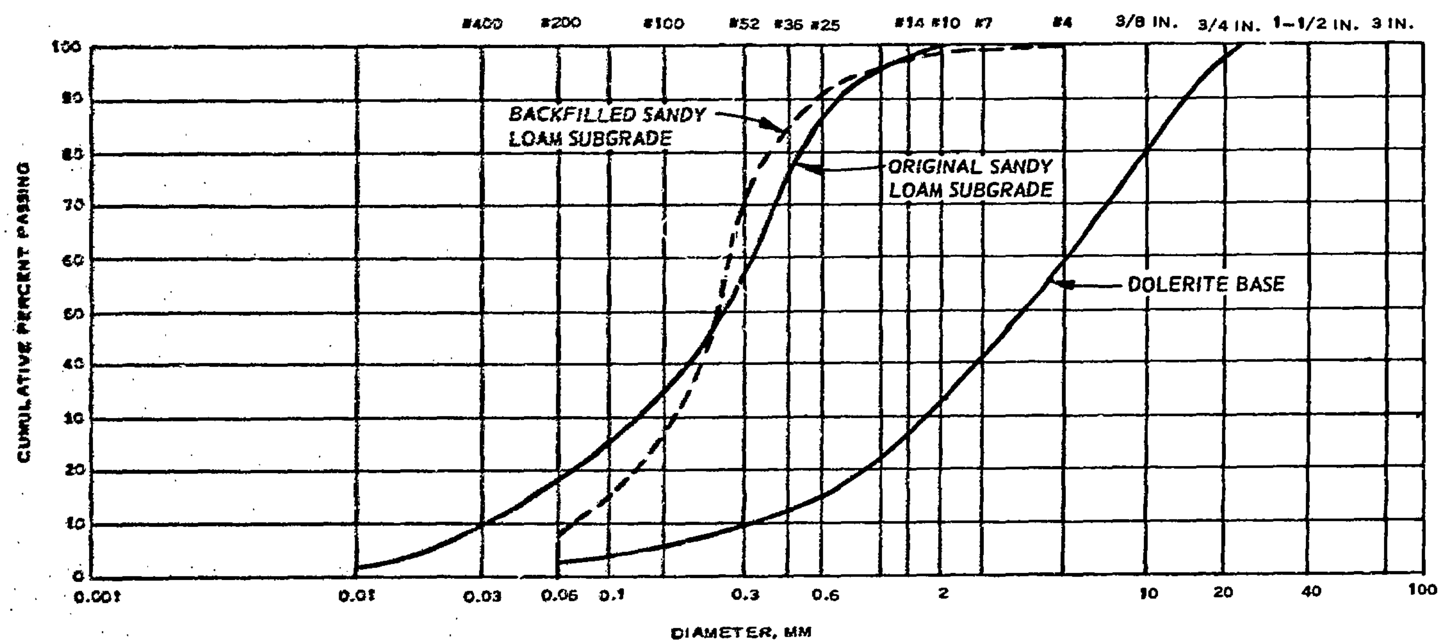
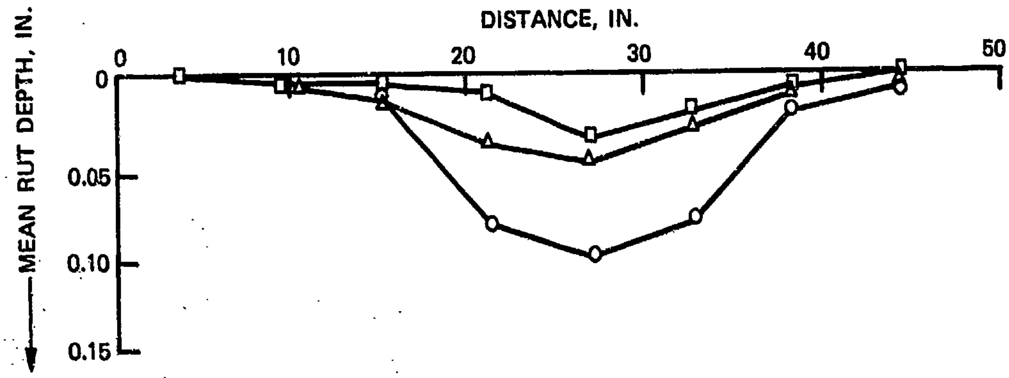
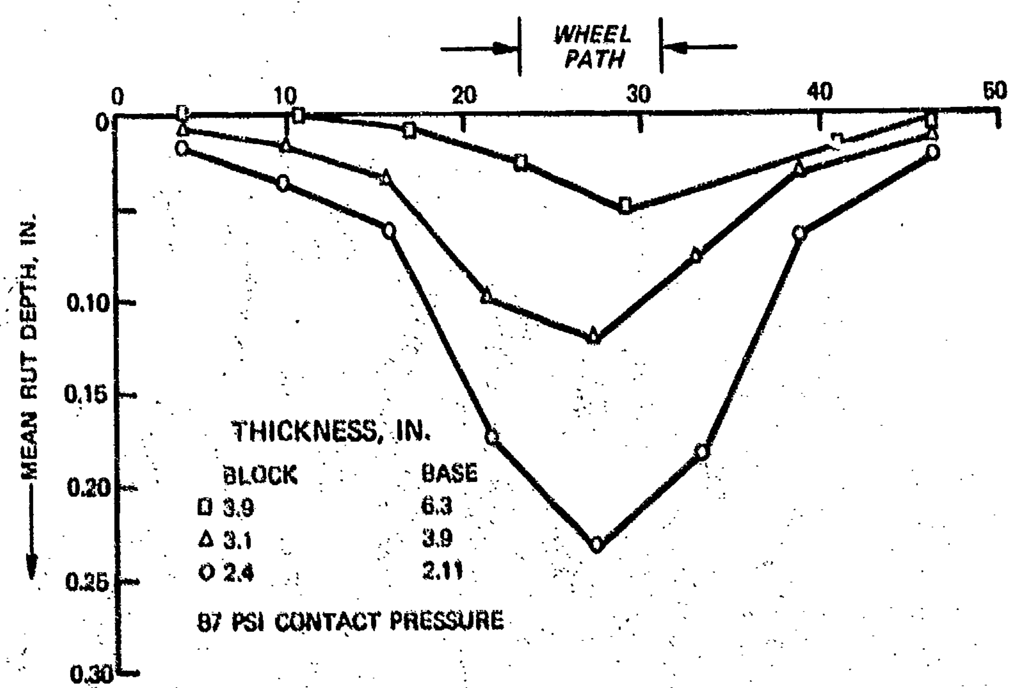


Figure 33. Gradation curves for road simulator test (Shackel 1978)



a. 1,000 repetitions



b. 13,000 repetitions

Figure 34. Typical transverse rut profiles from road simulator tests (Shackel 1978)

thickness; typical examples* of these for the 87-psi load are:

$$\log(\text{rut depth}) = 3.867 - 0.988 \log(\text{block thickness}) - 0.875 \log(\text{base thickness})$$

correlation coefficient (r) = 0.82

or

$$\log(\text{stress at subgrade surface}) = 3.866 - 0.495 \log(\text{block thickness}) - 0.517 (\text{base thickness})$$

$$r = 0.93$$

108. After the tests to investigate relationships among block thickness, base thickness, and loading pressure, another series of tests evaluated the effect of block shapes. These tests found no significant difference in performance between different interlocking shaped blocks, but, as shown in Figure 35, rectangular blocks had somewhat greater rut depths than shaped blocks.

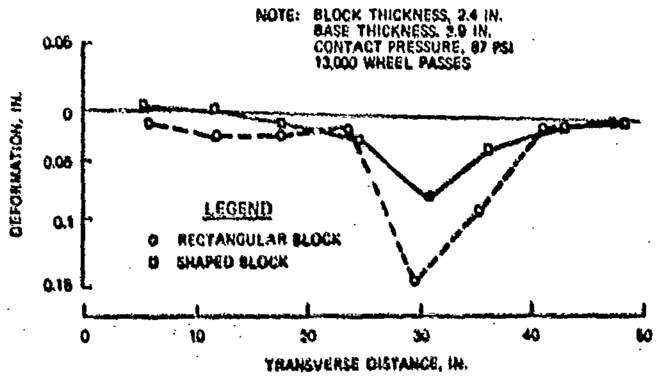


Figure 35. Effect of block shape on deformations in the road simulator (Shackel 1978)

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* These equations are shown in their original form developed using SI units of measure. The tests used loading pressures of 600 and 900 kPa, block thickness of 60, 80, and 100 mm, and base thickness of 60, 100, and 160 mm. Units for these equations are millimetres for depth and thickness and kilopascals for stress.

109. Another test examined the effect of reducing the loose laying course sand thickness from 2.0 to 1.2 in. As shown in Figure 36, this led to a large reduction in permanent vertical deformations. There was little effect on resilient deformation, but the measured pressure in the subgrade increased from about 7 psi to 11 psi when the sand layer thickness was reduced.

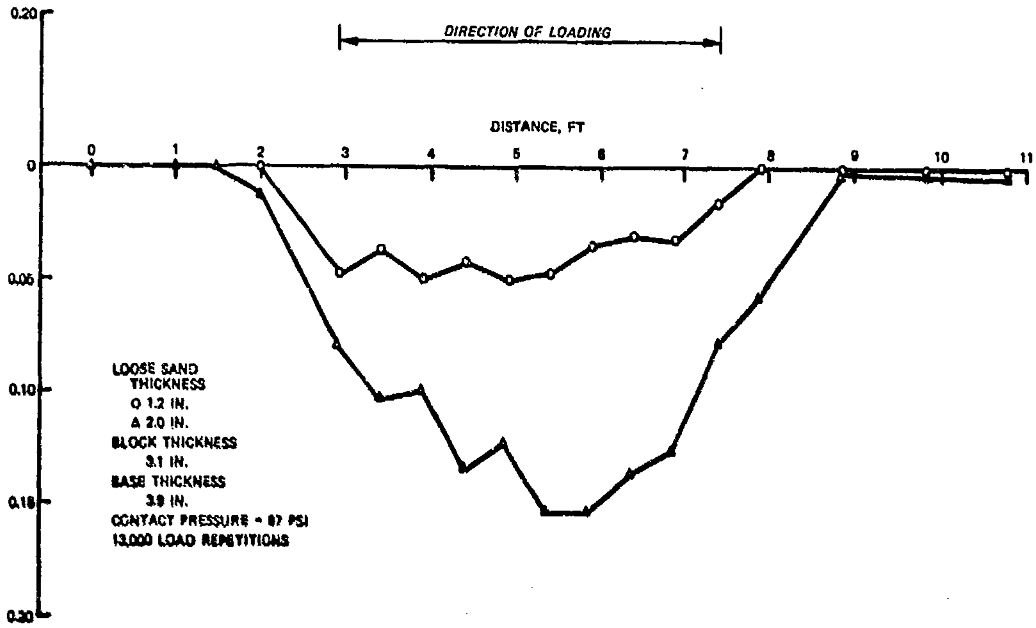

Figure 36. The effect of the sand layer thickness on permanent vertical deformations (Shackel 1978)

110. Some of the conclusions (Shackel 1978) drawn from this study are:

- a. Concrete block pavements tend to perform as flexible pavements.
- b. Block pavements stiffen with increasing traffic and achieve a "shakedown condition" after which further accumulation of deformation is negligible.
- c. An increase in block or base thickness improves performance.
- d. Increases in block thickness are more significant than increases in base thickness.
- e. An increase in block thickness from 2.4 in. to 3.1 in improves performance more than an increase from 3.1 in. to 3.9 in.

111. These extensive tests and conclusions reported by Shackel and Arora (1978a) and Shackel (1978) are strongly influenced by the strong subgrade used. The dominant vertical deformation measured in the tests must have come from densification rather than from shear movement. This belief is supported by several factors. Shackel (1978) states that "except after the initial test (i.e., using those pavements in Figure 32) it was not possible to detect any significant rutting in the dolerite base which could account for the development of the surface rutting along the simulated wheel paths." An examination of the transverse surface profiles in Figures 34 and 35 shows a general surface settlement without any characteristic shear upheaval outside the loaded areas. The reported mean dry density of the dolerite bases was 151.1 lb/ft^3 (Shackel 1978) or 101 percent of the modified AASHTO optimum reported by Shackel and Arora (1978b). The original sandy loam subgrade mean dry density was reported as 120.5 lb/ft^3 (Shackel 1978) or 95.7 percent of the modified AASHTO optimum reported in Shackel and Arora (1978b). The backfill sandy loam subgrade had a reported mean dry density of 104.9 lb/ft^3 (Shackel 1978). No compaction test data are reported for this material except for the statement that the modified AASHTO density for the backfilled sandy loam was lower than the original material but relative compaction levels were similar (Shackel 1978). To prevent densification under traffic, current U. S. Army Corps of Engineers criteria (Department of the Army 1971) would require a minimum 4-in.-thick base compacted to a minimum 100 percent of CE-55 density (equivalent to modified AASHTO) and a 100 percent CE-55 density in the backfill sandy loam. These Corps compaction criteria suggest that densification under traffic would occur in the sandy loam.

112. The small measured surface deformations considered with the high CBR subgrade, Shackel's reported observations on rutting, the shape of the transverse profiles, sandy loam compaction levels, and the relatively large deformations discovered in the 2-in.-thick loose sand laying courses all strongly suggest that densification and not shear was the primary cause of surface deformations. Therefore Shackel's (1978) regression equations and conclusions cannot be applied to block pavements

where shear deformations are occurring or compaction levels are different from those used in these tests.

Australian Road
Research Board Test Road

113. Sharp (1980) described a concrete block test road being built at the Melbourne headquarters of the Australian Road Research Board (ARRB). Ten test sections 13.1 ft wide and 32.8 ft long are being constructed between two parking lots used by the ARRB staff. The road will function as a minor residential road and is instrumented with pressure cells and moisture gages. Extensive surveys are planned for road user reactions (tire noise and roughness), surface deformations, skid resistance, and surface permeability. The test sections are designed to evaluate effects of block thickness, base thickness, compaction levels, and moisture content in the subgrade and base. The monitoring of the test road began in 1981 (Australian Road Research Board 1981).

South African Tests, Heavy Vehicle Simulator

114. In 1979, the South African National Institute for Transport and Road Research conducted a pilot study of the performance of interlocking concrete block pavements under the traffic of the Heavy Vehicle Simulator. Shackel (1979, 1980a) reported the results of this investigation which studied the effects of block shape, block strength, laying pattern, and block thickness.

115. Figure 37 shows the shapes of the blocks tested in this program. The blocks were laid on a 0.8-in.-thick layer of sand under which lay a 3.9-in. base course of poor quality natural gravel and a subgrade with an average CBR of 20 percent (Shackel 1980b). Properties of the subgrade, base, and sand layer are summarized in Figure 38 and Table 15. Blocks were laid by hand, vibrated with a vibratory plate compactor, and then revibrated as sand was swept into the joints. The quality of block laying in terms of joint width and uniformity was considered inferior to Australian or European standards but representative of South African laying standards (Shackel 1979). Edge restraint for the block pavements

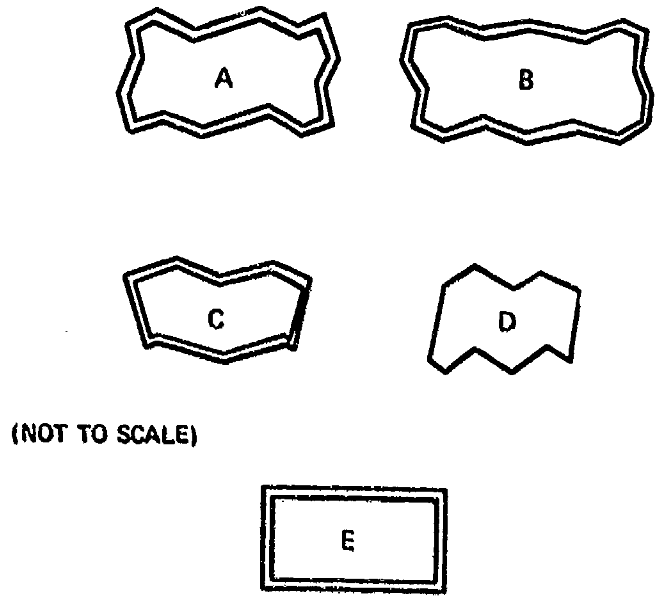

Figure 37. Block shapes tested (Shackel 1979)

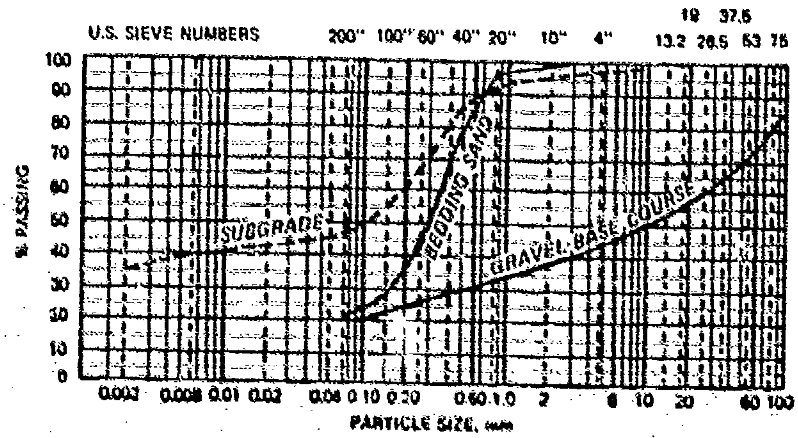

Figure 38. Gradation curves for the pavement materials (Shackel 1979)

was provided by reinforced concrete curbs. Each test section was 49.2 ft long and 9.8 ft wide.

116. The Heavy Vehicle Simulator used in these tests can apply loads from 4,500 lb to 17,980 lb on a single wheel along a 19.7-ft length. For these tests, traffic was uniformly distributed over a 2.95-ft-wide path. The load tire was inflated to 87 psi, which gave a

contact area of 112.5 $in.^2$ at a load of 8,990 lb. The wheel traversed the test sections at a speed of 2.2 mph. During the trafficking of the test sections vertical deformations of the surface and pressure cell loadings were measured.

117. Figure 39 shows that block types C, D, and E of Figure 37

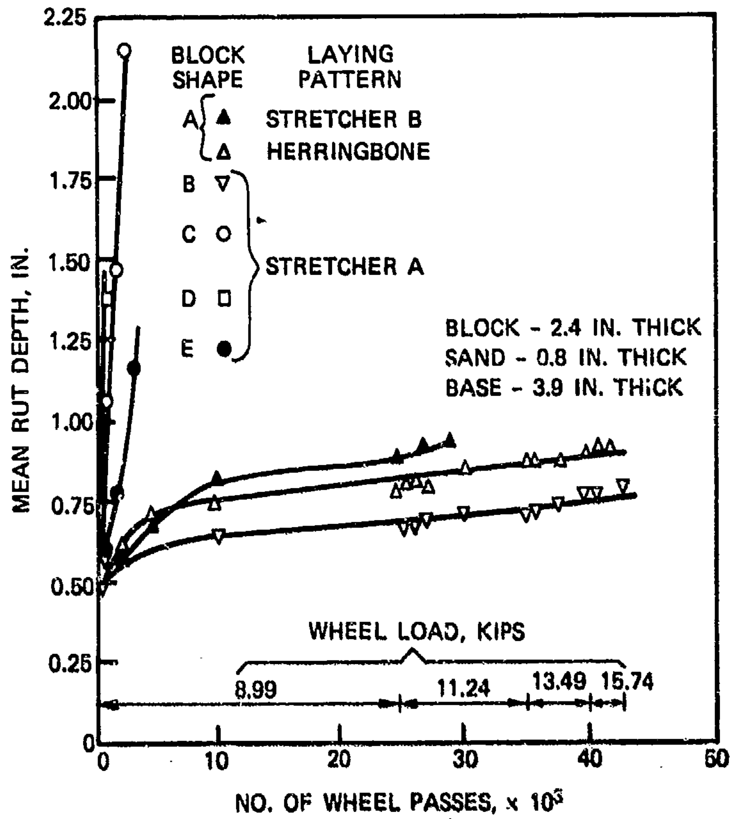

Figure 39. Comparison of performance by block shape (Shackel 1980)

failed rapidly under the 8,990-lb wheel load, while type B was adequate through the 11,240-lb load and type A was adequate through the 15,740-lb load. Stretcher bond A in Figure 39 is the conventional stretcher bond laying pattern in Figure 3a with the long side of the block perpendicular to traffic. Stretcher bond B is the same pattern but with long side of the block parallel to traffic to simulate conditions at an intersection where traffic would cross the pavement at right angles to stretcher bond A.

118. After the rapid failure of blocks C, D, and E new identical test sections were constructed and trafficked with a load of 5,400 lb. Block E again failed very rapidly, and the results of the 5,400 lb and then progressively heavier traffic are shown in Figure 40. Table 16 summarizes the complete road simulator tests as reported by Shackel (1979).

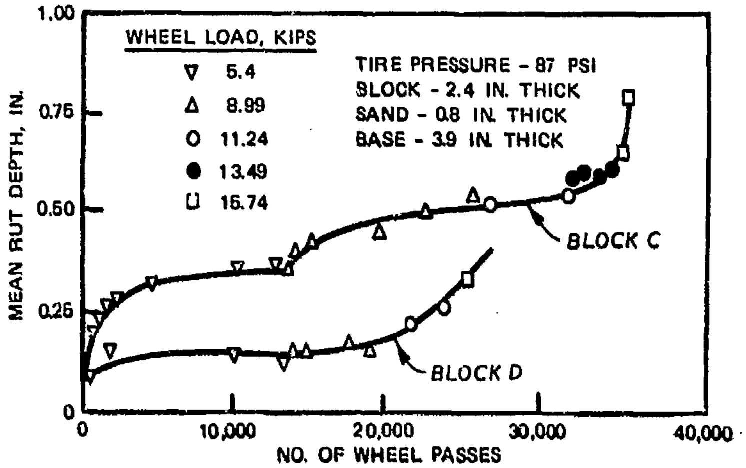

Figure 40. Effects of accelerated trafficking on block types C and D (Shackel 1980)

119. Shackel (1979) concluded from the results of these tests:

a. Block pavements tend to perform similarly to conventional flexible pavements.

b. Most of the block pavements exhibited a progressive stiffening with traffic; i.e., the rate of deformation decreased.

c. Pavements of block types A and B tended to achieve an interlocked condition beyond which deformation accumulation was very slow.

d. Once interlock had been achieved, increases in wheel load had little effect on deformation.

e. The shape of a paving block affects its ability to achieve interlock and support a given wheel load, as well as affecting pavement performance.

f. Shaped block perform better than rectangular blocks.

g. Pressure cell measurements indicate that the bedding sand layer contributes to the structural capacity of the pavement.

h. The herringbone laying pattern tended to perform better than stretcher bond A or B.

i. Block strength within the range of 3700 to 7980 psi compressive strength and 610 to 1150 psi flexural strength did not affect the pavement performance.

120. The variation in subgrade CBR between values of 6 and 68 percent in Table 16 requires that conclusions c, d, e, f, and h be considered with some caution until further experimental verification is available. For instance, on the low CBR subgrades of 6 to 9 percent all blocks (type E rectangular, type C interlocking on two sides, and type B interlocking on four sides) failed under the 5,400-lb bond when they were laid in the stretcher bond A. At the higher CBR values of 21 and 25 percent the block types C and D that interlock on two sides outperformed the block type A that interlocks on four sides and that was also on a higher CBR of 40 percent. All were laid in stretcher bond A. Interlocking block types A and B were tested with either different laying patterns or significantly higher subgrade CBR values then blocks C, D, and E under the 8,990-lb load. At similar CBR values (21-28 percent) and with identical stretcher bond A laying patterns, the rectangular block E outperformed block D (interlocking on two sides) and equalled block C (interlocking on two sides). The importance of the subgrade CBR is further borne out by Shackel's (1979) description of failure of blocks C, D, and E under the 8,990-lb load: "Pavements quickly developed unacceptable degrees of rutting. As the rutting progressed, subgrade failures eventually occurred and were manifested as heaving along either side of the wheel path."

Danish Test Road

121. Lesko (1980) described a test road containing four sections of concrete block pavement near Viborg, Denmark. Figure 41 shows the four types of blocks included in the test road. In addition to the

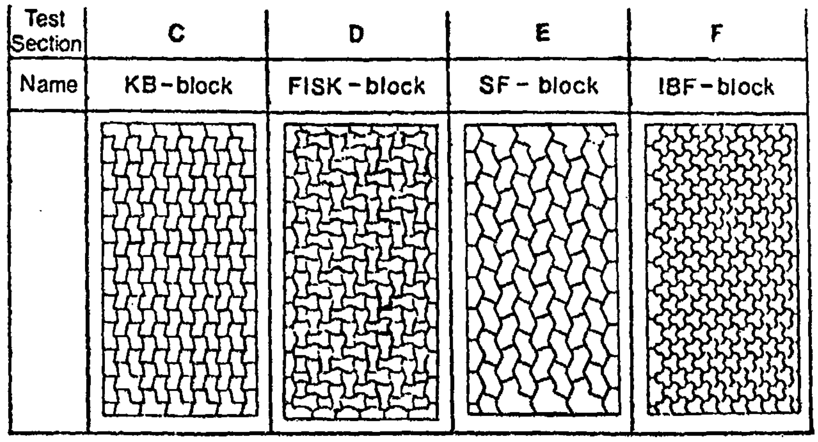

Figure 41. Blocks and laying pattern used in Danish test road (Lesko 1980)

block sections the test road includes two conventional asphaltic concrete sections and one section with an experimental asphaltic product.

122. Each block test item is 11.5 ft wide and 656 ft long. All blocks are 3.1 in. thick. The pavement structure above the subgrade consisted of a 15.7-in.-thick sand subbase, 3.9-in. granular subbase, 7.9-in. cement-stabilized granular base, 1.2-in. sand laying course, and the block surface. The cement-stabilized granular base contained 8 percent cement and had a 7-day compressive strength of 2,900 psi. Average block compressive strengths varied from 11,020 to 11,750 psi. The sand layer was compacted by a roller; next blocks were placed by hand. Sand was swept into the joints between blocks, and then the blocks were compacted with a vibratory plate and a small tandem wheel roller.

123. The test road was opened to traffic in October 1977. Lesko (1980) reports that the block pavements have shown satisfactory durability, but there were some settlements over transverse shrinkage cracks in the cement-stabilized material. This is believed to be due to erosion of the sand into the shrinkage cracks of the stabilized material. There have also been some sporadic settlements close to the edge of the pavement that are believed to be due to laying techniques or lack of edge support.

124. The thickness of the sand layer decreased to 0.8 in. after

2 years of traffic. There is also a slight tendency of joints in the wheel pattern to widen slightly. The depth from the surface of the block to sand in the joint is 0.4 in. in the wheel path compared to 0.2 in. outside the wheel path. Lesko (1980) concluded from the performance of this road that:

a. Bitumen or cement-stabilized sand should be used for the laying course.

b. In general the block pavements have performed remarkedly well.

c. It is doubtful whether block pavements can be constructed to a smoothness acceptable for main roads and motorways, but block pavements can find extensive use in low-speed pavements.

PART VI: WES TEST SECTION

Objective

125. In August 1979, the Waterways Experiment Station built and tested a concrete block pavement test section. The objectives of the test were to demonstrate the ability of block pavements to support heavy truck traffic on a weak subgrade and to collect performance data to help evaluate potential design methods for block pavements.

Test Section Description

126. The test section consisted of three test items each 15 ft wide and 20 ft long. The native lean clay, classified as CL in the Unified Soil Classification System, was excavated to a depth of approximately 24 in. A plastic clay, known locally as buckshot clay and classified as CH, was placed and compacted to provide a low-strength test subgrade with a CBR of 3 percent. The excavation was lined with a polyethylene sheet prior to placing the buckshot clay to help prevent the clay from drying out and increasing in strength during the test. Items 2 and 3 had a 4-in.-thick subbase of gravelly sand and a 4-in.-thick base course of crushed limestone above the buckshot clay. Item 1 had a 4-in.-thick base course of crushed limestone placed directly on the buckshot clay. All three items had a laying course of sand approximately 1 in. thick, and the test items were surfaced with different types of block. Lateral restraint for the blocks was provided by 10-ft-long, 4-in.-wide, 6-in.-deep oak timbers. These timbers were on all four sides of each test item and each timber was anchored to the ground with three 24-in.-long steel pins (Figure 42). Figure 43 shows a cross section of the test section showing the three different test items.

127. The three types of blocks used in these tests are shown in Figure 44. Item 1 used a Z-shaped block ("No. 1" in Figure 44) that was 3.1 in. (80 mm) thick; item 2 used a rectangular block ("No. 2" in

Figure 42. Timbers and pins used for edge restraint

Figure 44) that was also 3.1 in. (80 mm) thick; and item 3 used a shaped block ("No. 3" in Figure 44) called Unistone that was 2.4 in. (60 mm) thick. Table 17 shows the results of laboratory tests on the blocks. The blocks used in this test section were all of high quality and strength.

128. Figure 45 shows the gradation, soil classification, and Atterberg limits for the buckshot clay, gravelly sand, and crushed limestone. The buckshot clay is a dark brown backswamp deposit of the Mississippi River and has been used extensively in pavement investigations at the Waterways Experiment Station. Figure 46 shows the compaction curves for this material. Also plotted on these laboratory curves are field data from the test section. These data points are identified as "construction field data," "field data outside traffic lane," or "field data inside traffic lane." The construction data are quality control tests run during construction of the test section. The other data were collected from pits dug after traffic on the test section was completed. The inside traffic lane data were collected beneath the traffic-loaded

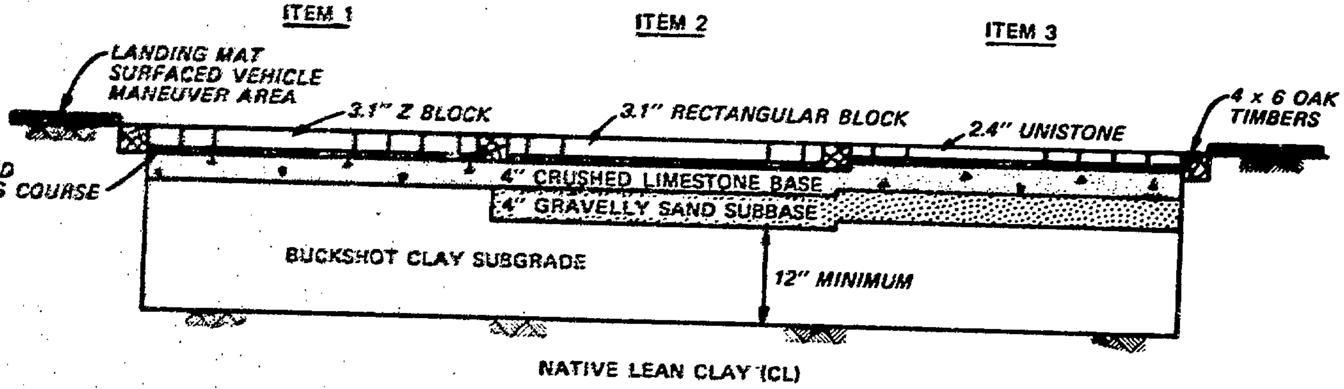

Figure 43. WES test section cross section

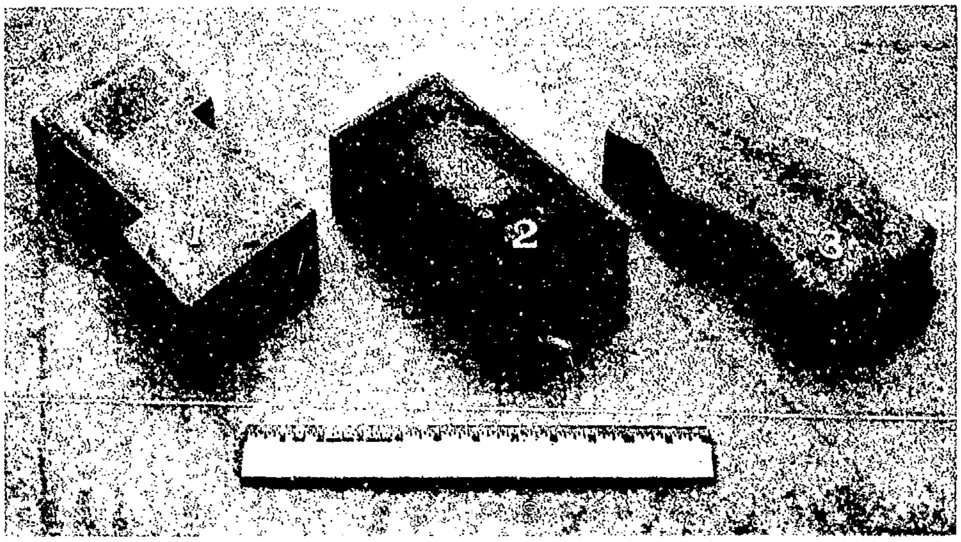

Figure 44. Block shapes used in WES test

portion of the pavement; the outside traffic lane data were collected under untrafficked portions of the test section. The field data densities show some scatter, but there is no trend suggesting that compaction of the clay occurred during traffic. Two field CBR tests in Figure 46 show some drying with an accompanying increase in CBR and are from the buckshot clay surface in item 1. All other field CBR data points, including tests run 6 in. below the buckshot clay surface in item 1, maintained a CBR of 3 to 4 percent. The buckshot clay successfully provided a consistently weak subgrade with a CBR of 3 to 4 percent throughout the test. The effect of surface drying in item 1 will be discussed in more detail later.

129. The gravelly sand used in the subbase is a local alluvial material with smooth rounded particles. Maximum density for this material in Figure 47 is at saturation, which is typical of cohesionless soils. This gravelly sand meets the Corps of Engineer requirements (Department of Defense 1978) for a flexible pavement subbase with a design CBR of 50 percent.

130. The base course for all test items was crushed, well-graded limestone. The compaction curve for this material is shown in Figure 48 and shows an optimum CE-55 density of 147.6 lb/ft^3 at an optimum

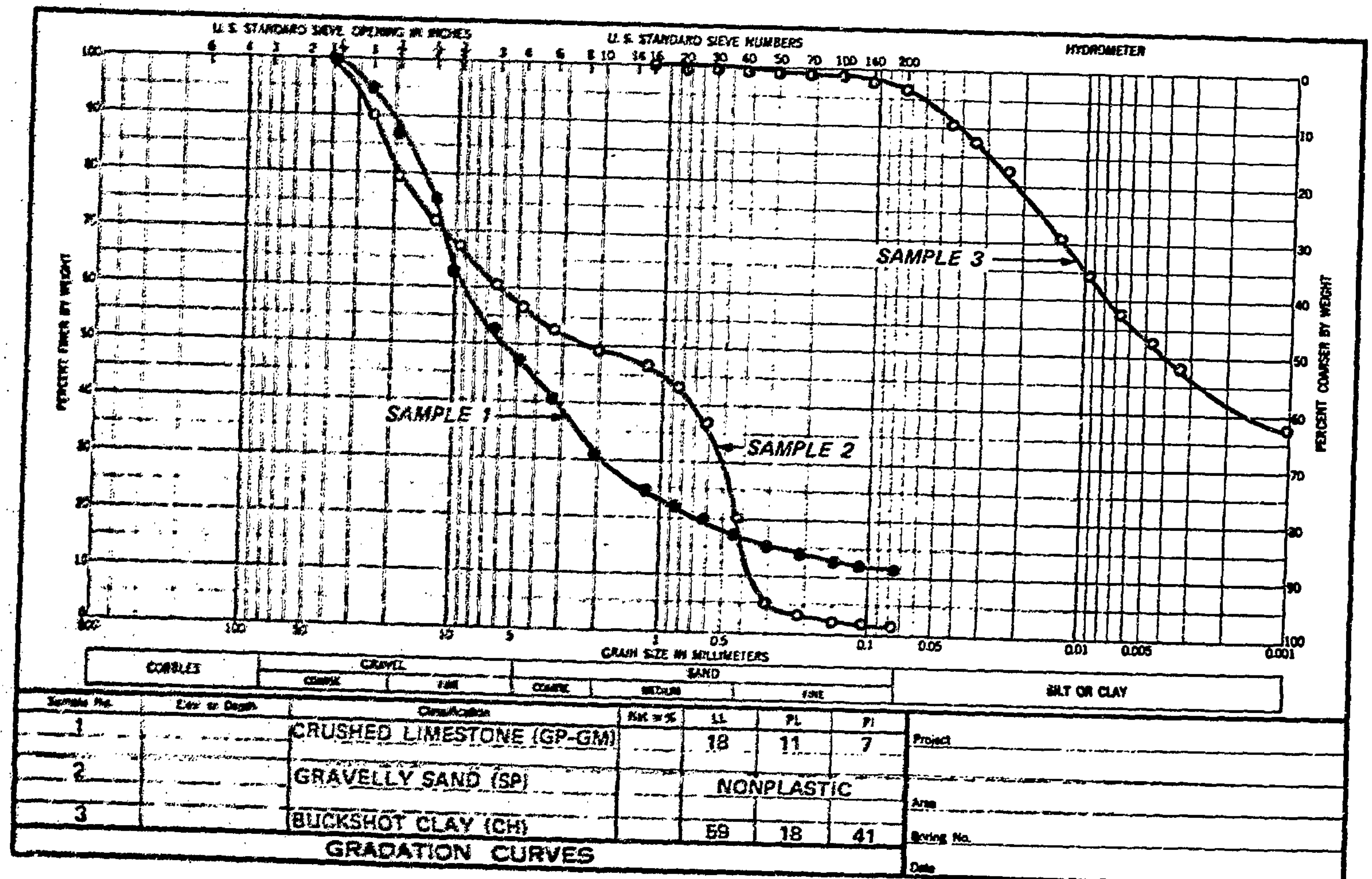

Figure 45. Soil gradations in WES test section

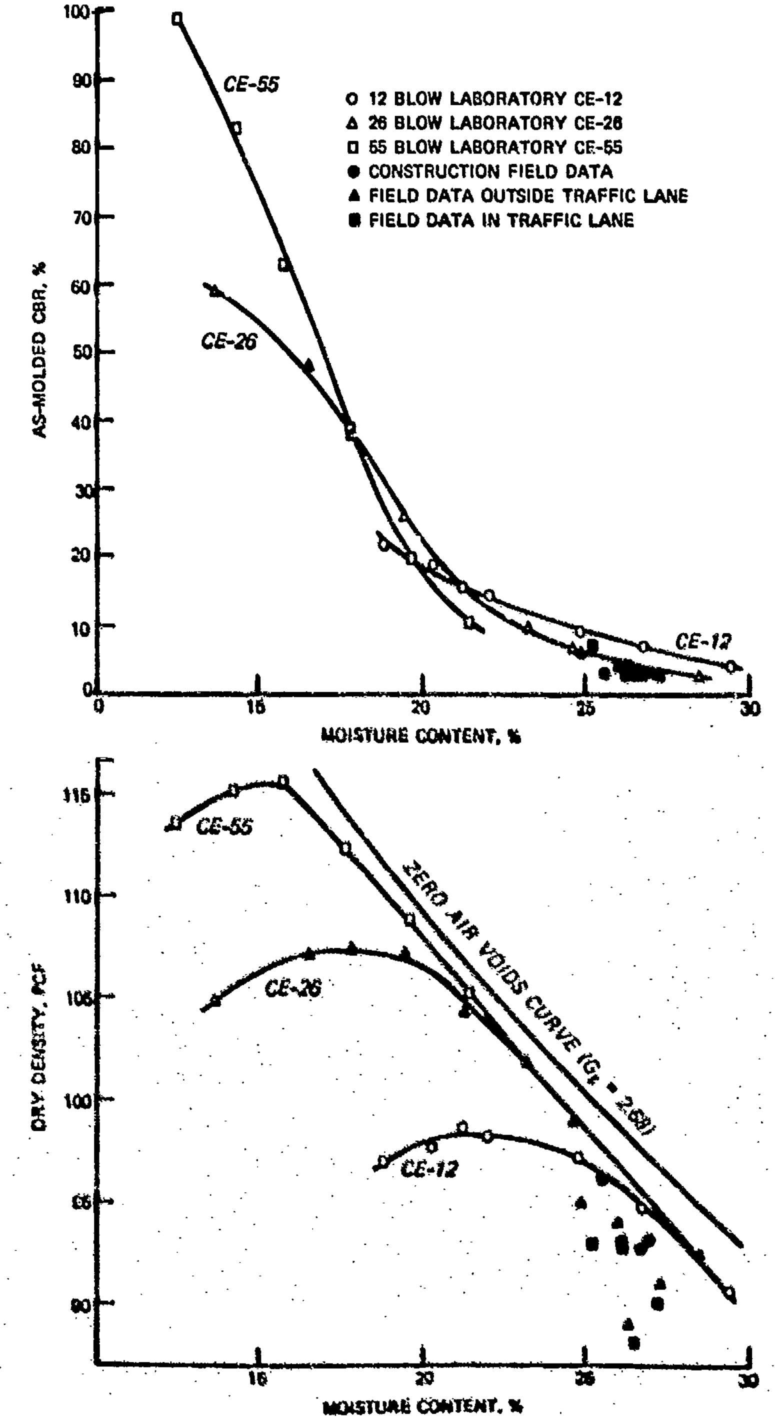

Figure 46. Buckshot clay compaction and CBR curves

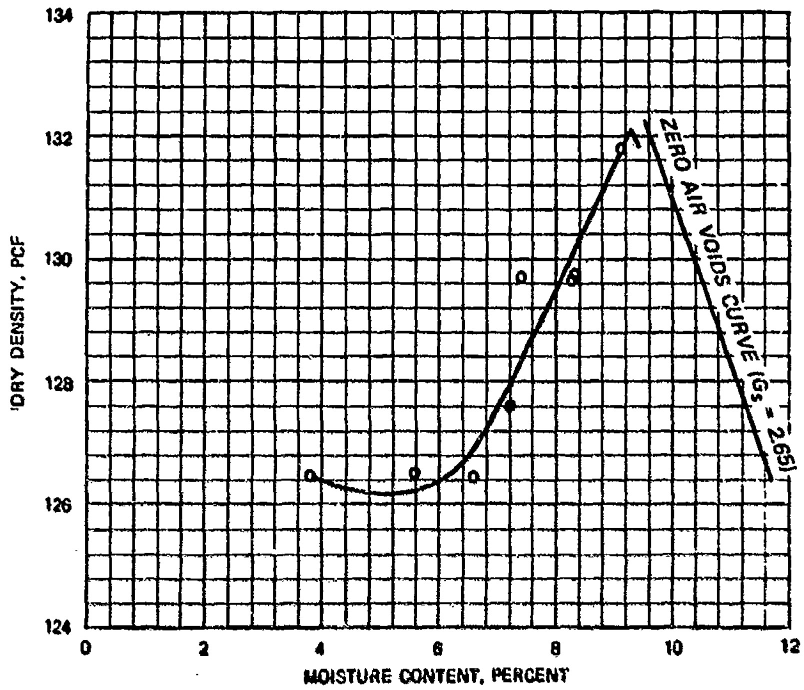

Figure 47. CE-55 compaction curve for gravelly sand

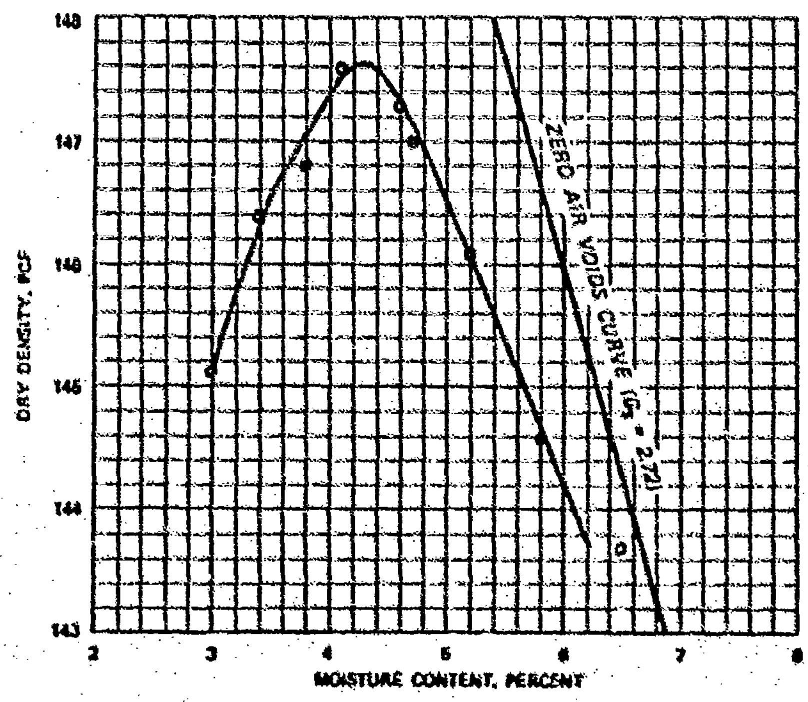

Figure 48. CE-55 compaction curve for crushed limestone

moisture content of 4.3 percent. Laboratory CBR values for this material consistently exceeded 100 percent. This material did not meet the Corps of Engineers requirements (Department of Defense 1978) for a crushed stone base course material with a design of 100 percent because the plasticity index of 7 exceeded the maximum permissible value of 5 and the 12 percent passing the No. 200 sieve (Figure 48) exceeded the maximum permissible value of 10 percent. However, these requirements are primarily to limit the susceptibility of the base material to water. Since the block pavement test section was inside of WES Hangar No. 4 and was not subjected to rain, these deviations in base quality are not important for this test.

Construction Procedures

131. The buckshot clay was spread and leveled in 6-in. lifts with a Caterpillar D-4D-tracked dozer. Each lift was compacted with 8 coverages of a self-propelled Ingram pneumatic roller (Figure 49). The

Figure 49. Rolling of heavy clay subgrade, 8 coverages, 65-psi tire pressure, 34 kips

roller had seven smooth tires inflated at 65 psi and a gross load of 34,000 lb. The quality control data collected during construction found dry densities to be slightly over 80 percent of CE-55 density and CBR values consistently at 3 percent.

132. The gravelly sand and crushed limestone were spread and leveled with a motor grader. Each layer was compacted with a self-propelled Rex 700 vibratory roller (Figure 50). This machine has a

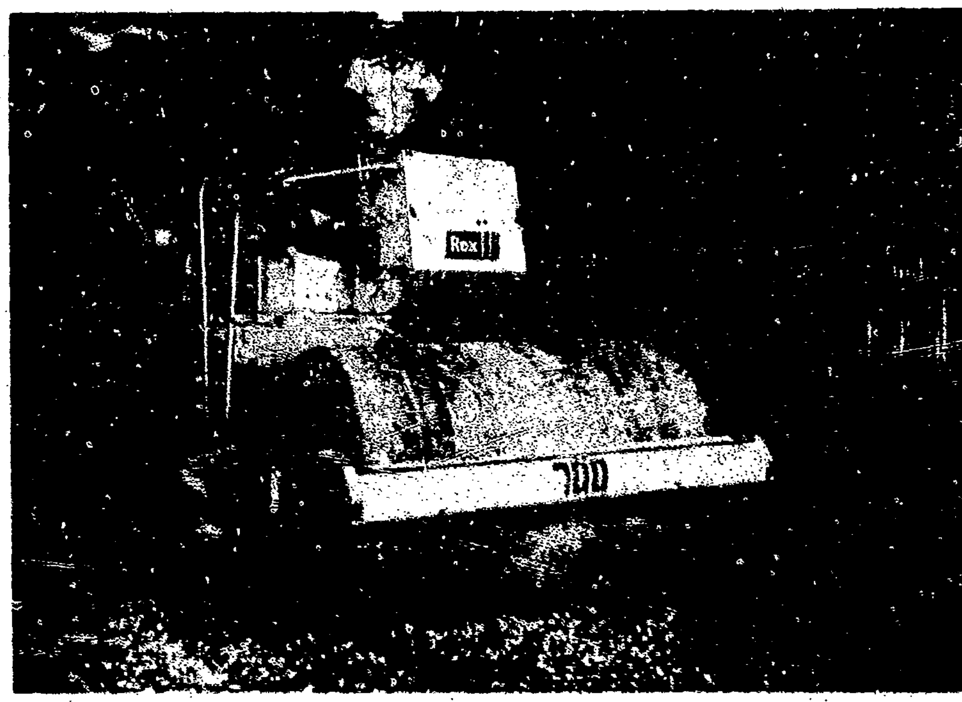

Figure 50. Rolling of limestone base with steel-wheel vibratory roller at approximately 14-kip dynamic force

gross static weight of approximately 14,000 lb and was operated at the manufacturer's dynamic force rating of 14 kips. Quality control data collected during construction found that gravelly sand densities were slightly above 95 percent of CE-55 density, and the crushed limestone was only about 90 percent. Repeated passes of the roller failed to improve these values. These low densities are due to the difficulty of compacting thin layers of material over resilient subgrades like the buckshot clay.

133. The sand laying course was a masonry sand that was screeded to a depth of approximately 1 in. (Figure 51). Block laying followed the procedures recommended by the National Concrete Masonry Association (1979) and was described in Part III of this report. The construction crew that built the test section had never worked with concrete paving block before but encountered no problems during construction. Figure 52 shows the completed test section with item 1 in the foreground.

Traffic

134. Traffic loads were applied by the tandem-axle truck shown in Figure 53. All traffic was low speed and estimated not to exceed 5 mph. The truck was loaded with lead ingots until the load on the tandem axle was 25,000 lb. Wheel spacing for the tandem axle is shown in Figure 54. Using the Corps of Engineers equivalency factors in Figure 55 (Brown and Ahlvin 1961), one pass of the 25,000-lb dual-wheel, tandem-axle load is equivalent to one pass of a standard 18,000-lb, dual-wheel, single-axle load.

135. The rope visible in Figures 52 and 53 marks the outside left lane of traffic for the driver. No prescribed width or distribution of traffic was used in applying traffic. The traffic distribution came from the natural driving variation of the driver as he tried to drive with the wheels adjacent to the marking rope. This led to a narrow trafficked width of approximately 34 in. for each set of dual tires.

136. Traffic on a pavement tends to follow a normal distribution shaped pattern within the trafficked area (Brown and Ahlvin 1961). Consequently, not all portions of the pavement receive the same number of passes or stress repetitions. Brown and Ahlvin (1961) developed a method for calculating the relationship between the number of passes of a vehicle and the coverages or maximum number of stress repetitions in the traffic lane. This relationship assumes a normal distribution of traffic and the other factors in the analysis are the wander of the vehicle in the traffic lane and the spacing and configuration of wheels and axles. For the truck used in this test the passes per coverage

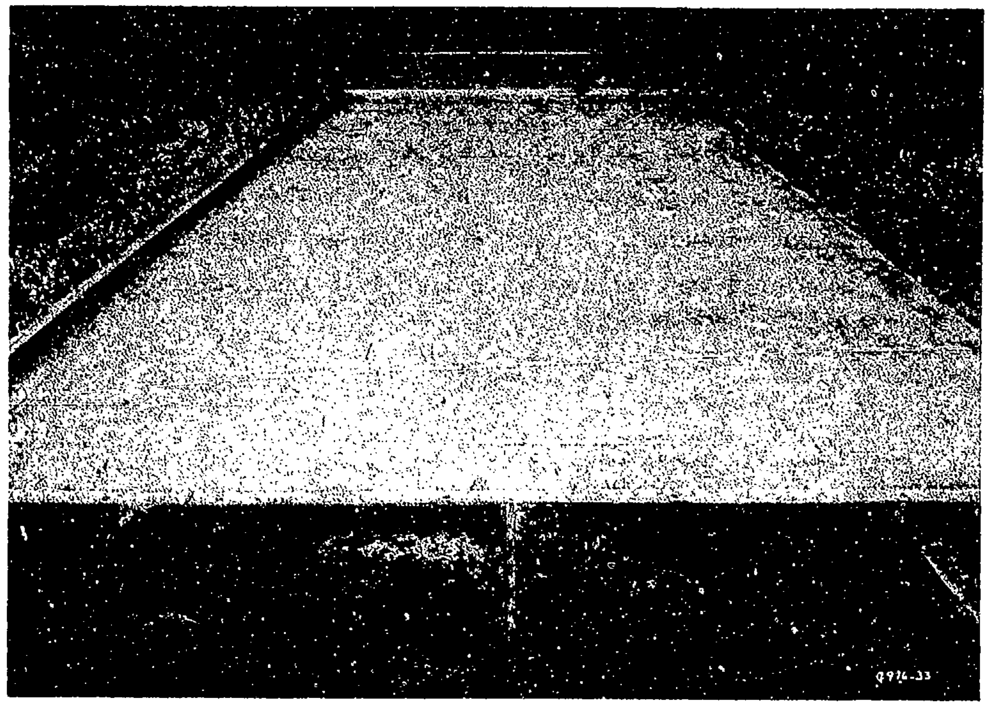

Figure 51. Screeded sand

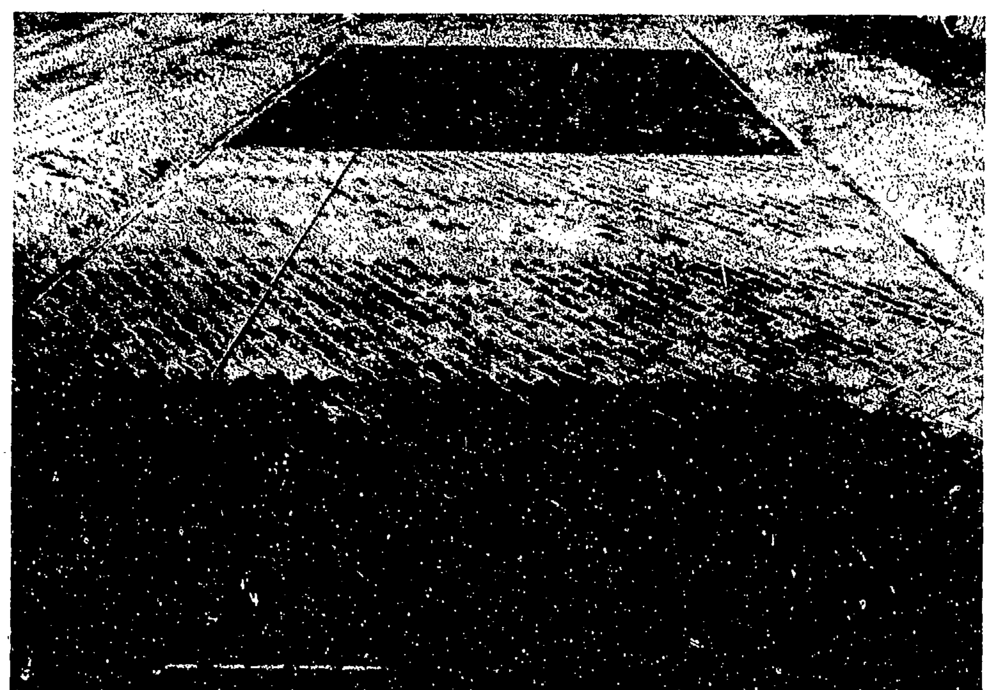

Figure 52. WES test section, items 1, 2, and 3 at 0 passes

Figure 53. Traffic vehicle

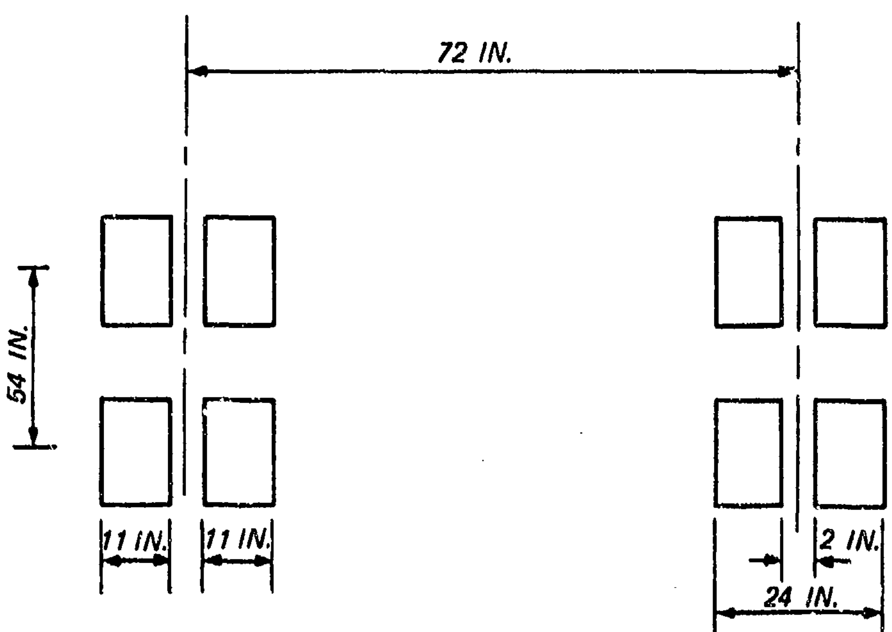

Figure 54. Tire spacing for 25-kip tandem axle

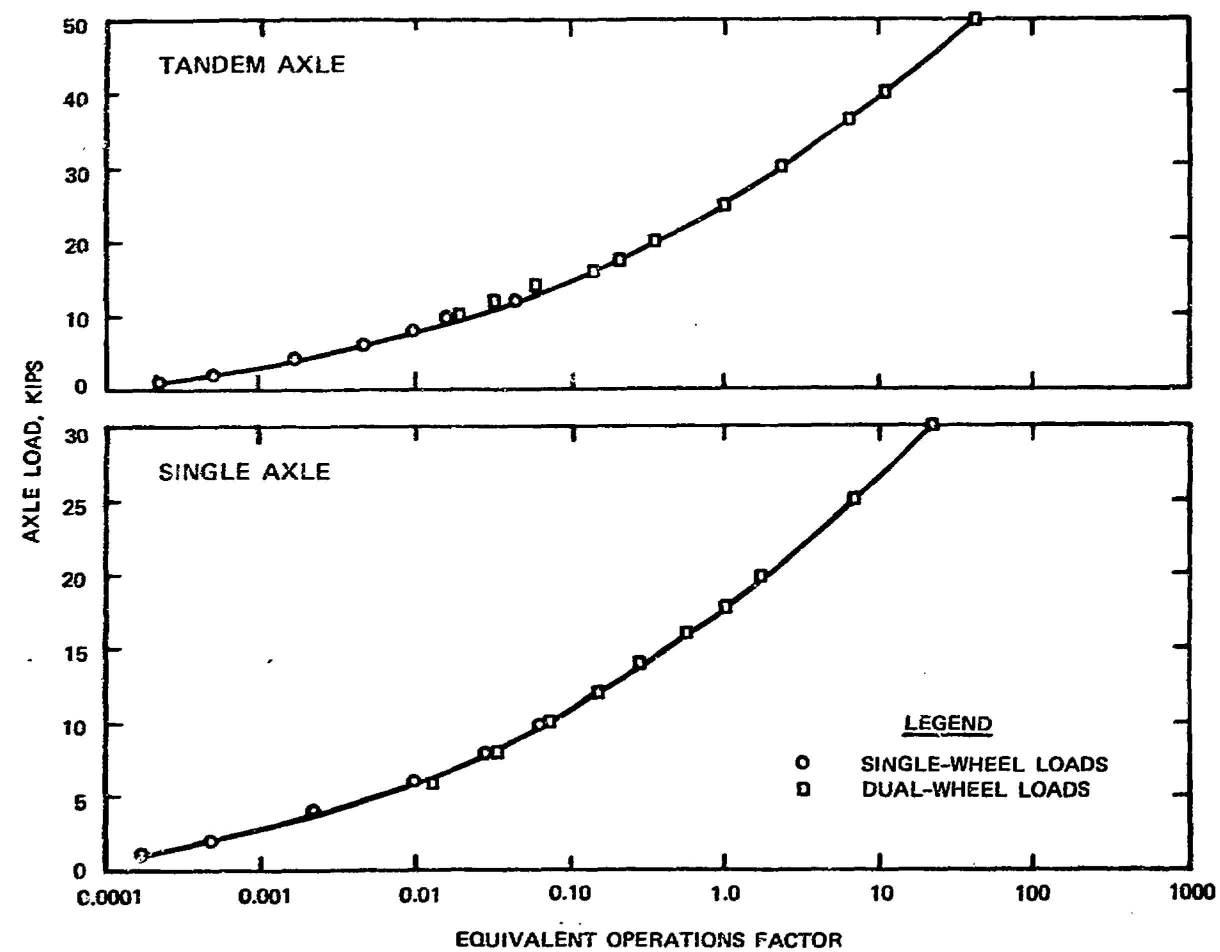

Figure 55. Corps of Engineers equivalent 18-kip operation factors

ratio is 1.05, or in the other words, the critical portion of the traffic lane which receives the maximum number of stress repetitions is loaded one time for every 1.05 passes of the test vehicle. All three test items received 7500 passes of the test vehicle so the maximum number of coverages or stress repetitions at one point in the traffic lane was 7143 (7500 ÷ 1.05).

Performance

137. Figure 56 shows item 1 before traffic, and Figure 57 shows the item after 7500 passes (7143 coverages) of the test vehicle. The item showed no sign of distress during traffic other than a few isolated minor spalls (Figure 58) on the corners of a few blocks.

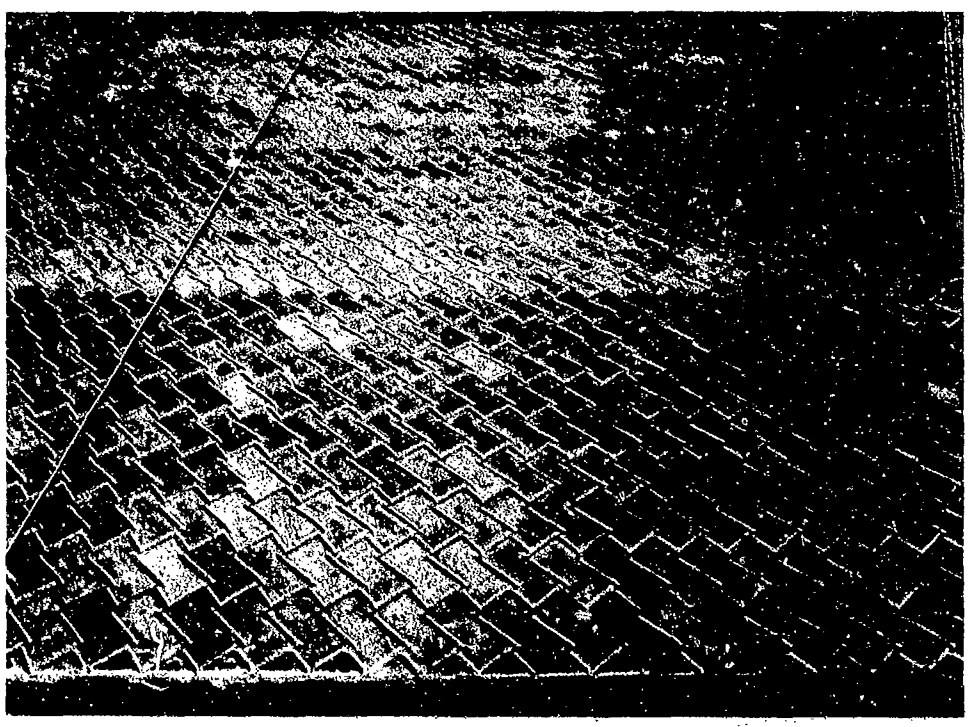

Figure 56. Item 1 at 0 passes

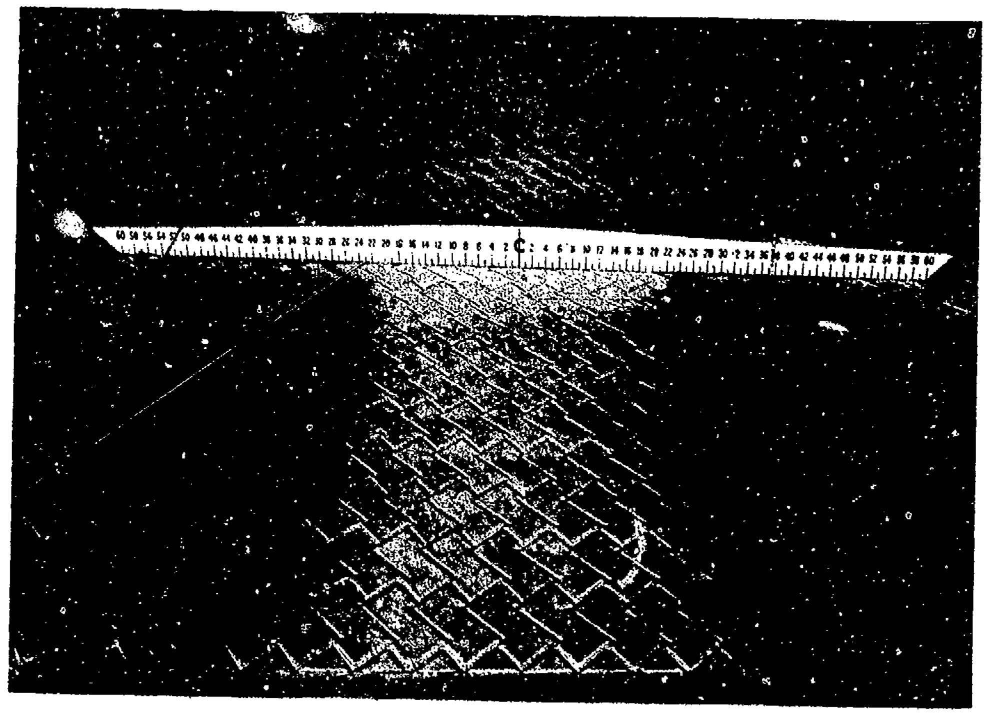

Figure 57. Item 1 at 7500 passes

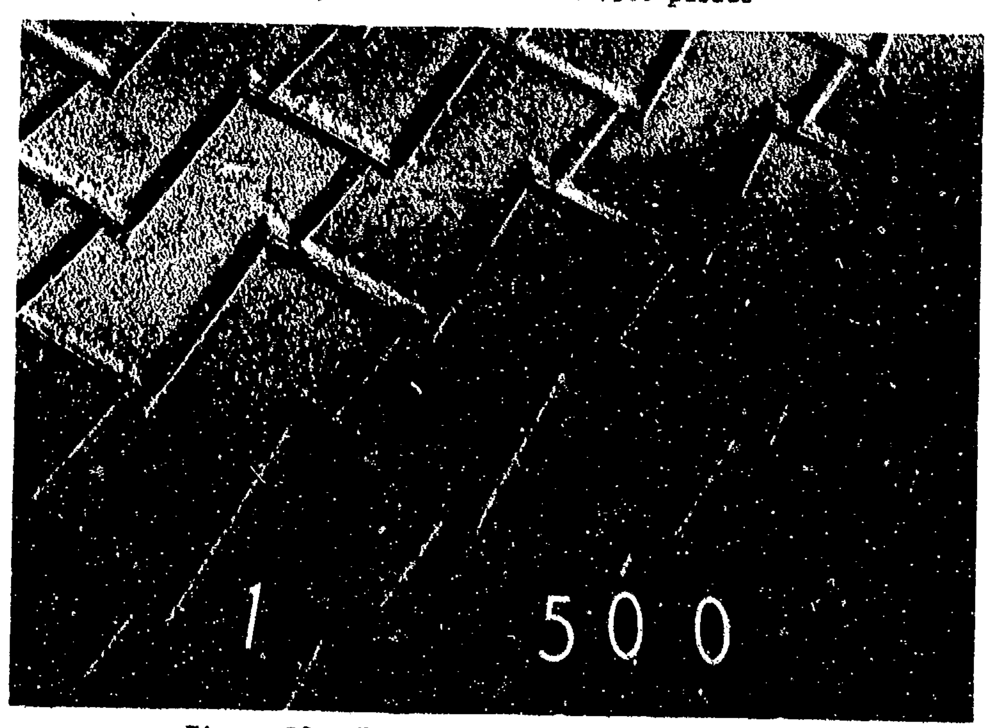

Figure 58. Item 1, corner break, 500 passes

138. Figure 59 shows item 2 before traffic. Some minor rutting is visible in Figu. · 60 after 1000 passes (952 coverages) and is more pronounced in Figure 61 at the end of traffic after 7500 passes (7143 coverages). Minor corner spalls such as shown in Figure 62 were more common in item 2 than item 1 but were still infrequent. Item 2 was still serviceable at the conclusion of traffic.

139. Figure 63 shows item 3 prior to traffic. Rutting is visible in Figure 64 after 500 passes (476 coverages) and is very pronounced in Figure 65 after 4000 passes (3810 coverages). Tilting of the individual blocks is visible in much of the traffic lane. The transition from the landing mat surfaced vehicle maneuver area and the block surface at the north end of the west wheel path (rear left side of Figure 65) has clearly failed and is undergoing major shear deformations. By 7500 passes (7143 coverages) in Figure 66 item 3 has deteriorated seriously. A close-up view of the north end of the west wheel path in Figure 67 shows the amount of surface deformation, block spalling, and block tilting that has occurred.

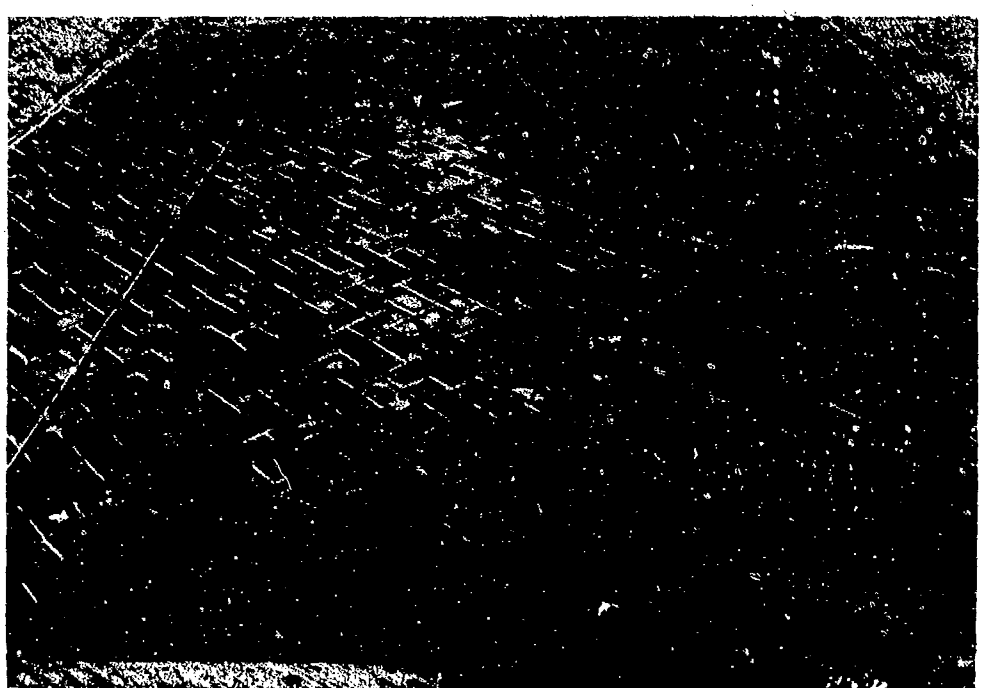

Figure 59. Item 2 at 0 passes

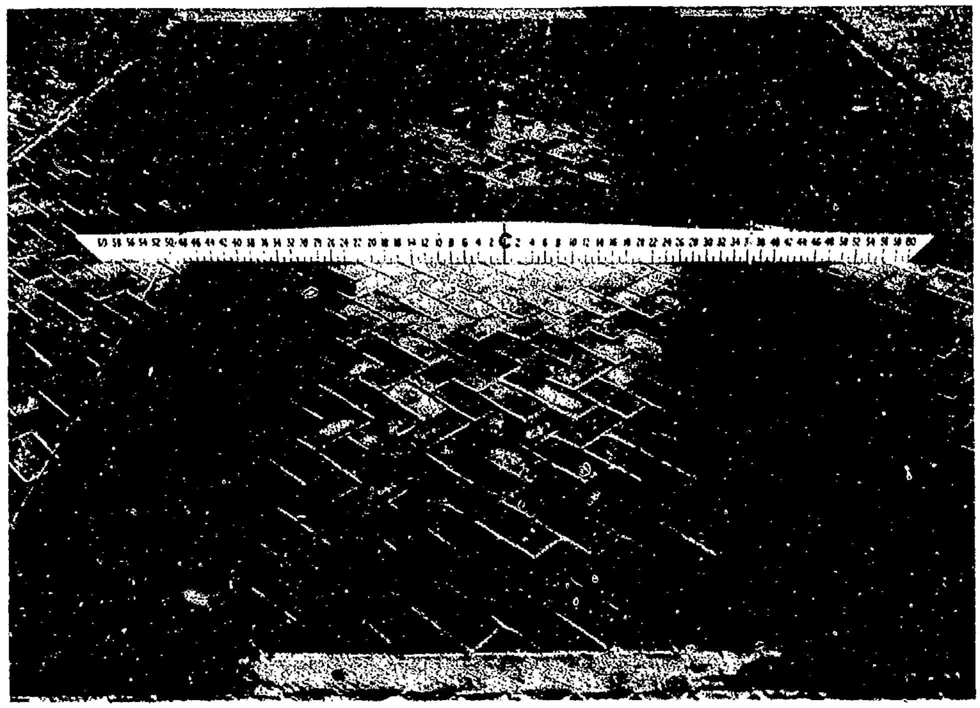

Figure 60. Item 2 at 1000 passes

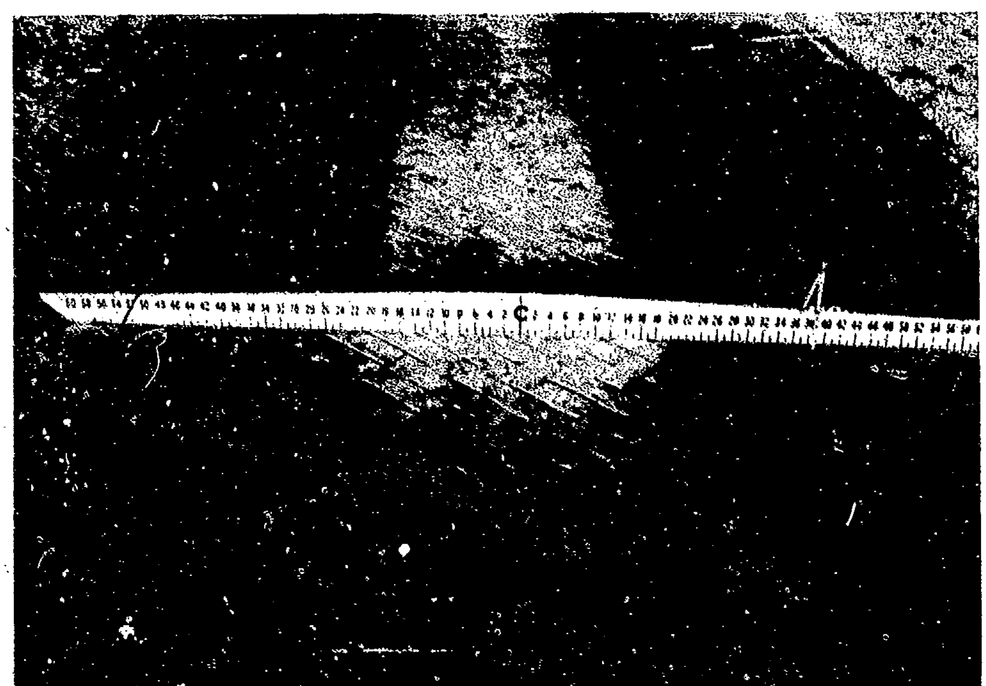

Figure 61. Item 2 at 7500 passes

Figure 62. Item 2, corner break, 3000 passes

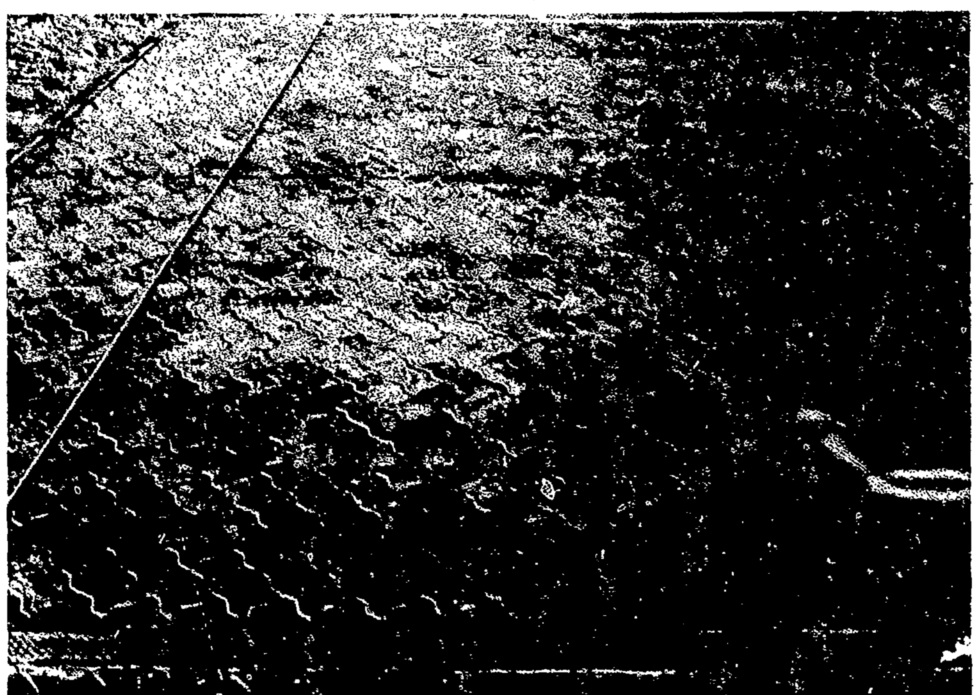
Figure 63. Item 3 at 0 passes

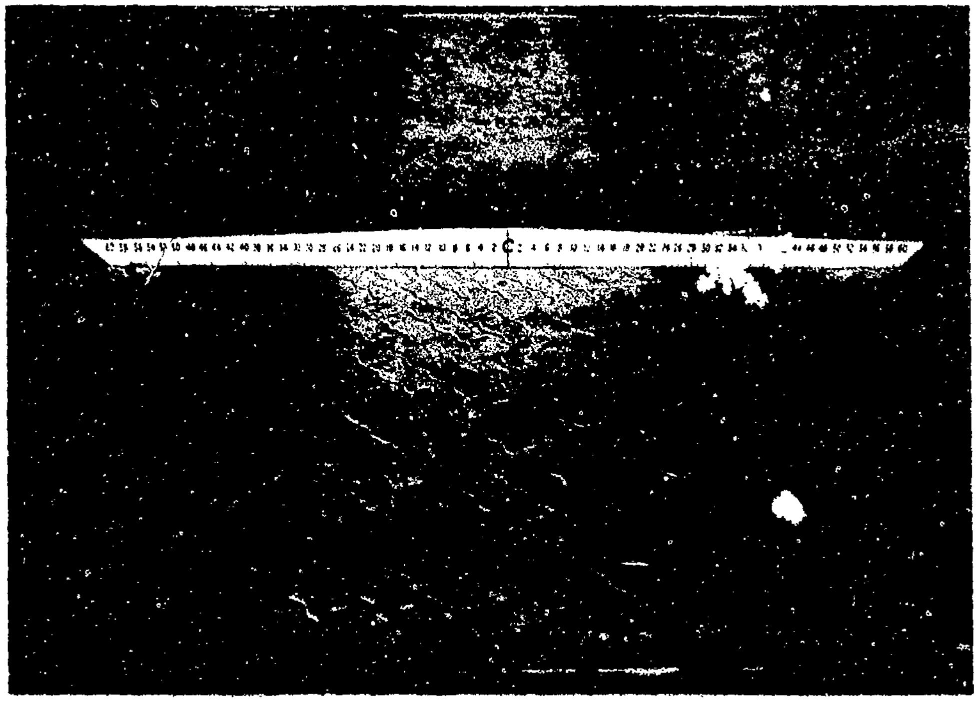

Figure 64. Item 3 at 500 passes

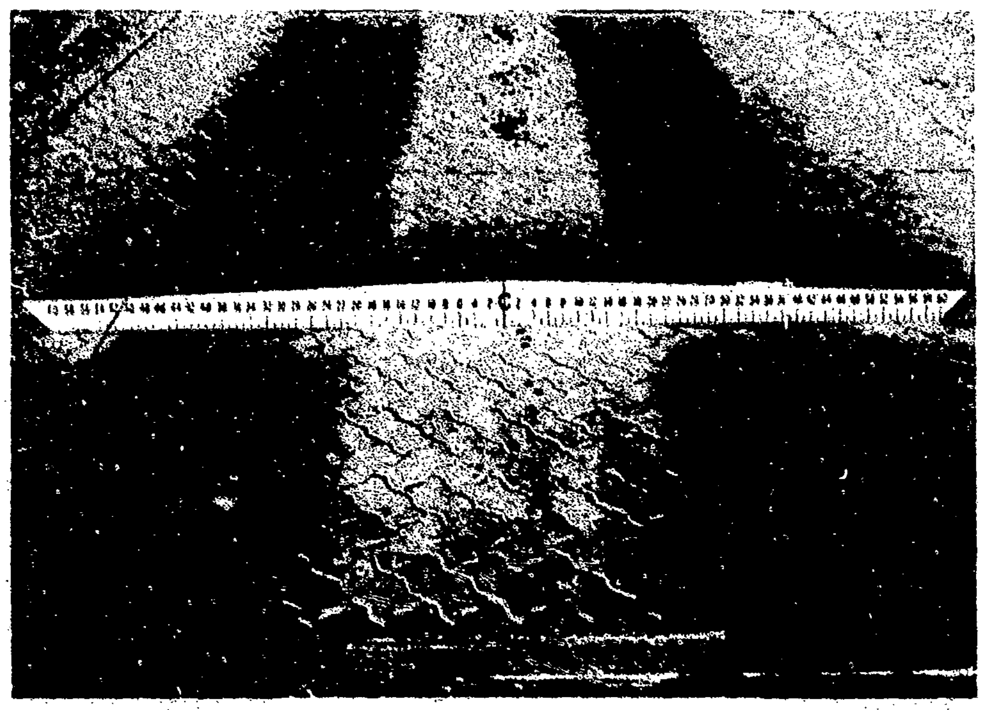

Figure 65. Item 3 at 4000 passes

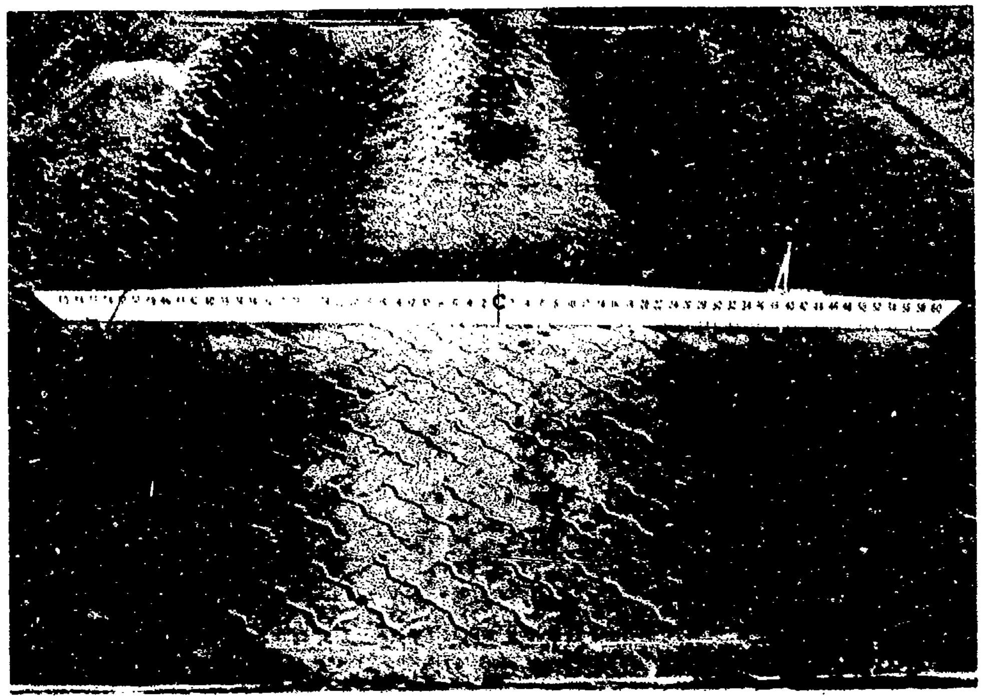

Figure 66. Item 3 at 7500 passes

Figure 67. Extreme rutting and block damage in item 3 at 7500 passes

140. After traffic with the truck, the M-48 tank in Figure 68 was turned repeatedly on the rectangular blocks in item 2. This tank was loaded with lead ingots for a total gross weight of 105,000 lb which is representative of a current U. S. Army M-60 tank. To make the turns, one track of the tank was locked while the other track drove the vehicle in circles. After repeated turns, blocks showed no signs of damage or shifting, and the test was halted.

Figure 68. M-48 tank on item 2

141. Profiles of the block surface were recorded across the transverse center line of each item and along the longitudinal center line of the east and west wheel paths. These profiles were recorded before traffic, at intervals during traffic, and at the conclusion of traffic. Similar profiles were collected before and after traffic on the surface of the base, subbase, and subgrade. These data are summarized in Figures 69 to 77.

142. During the construction of the test section, dry density, moisture content, and CBR values were recorded. At the conclusion of

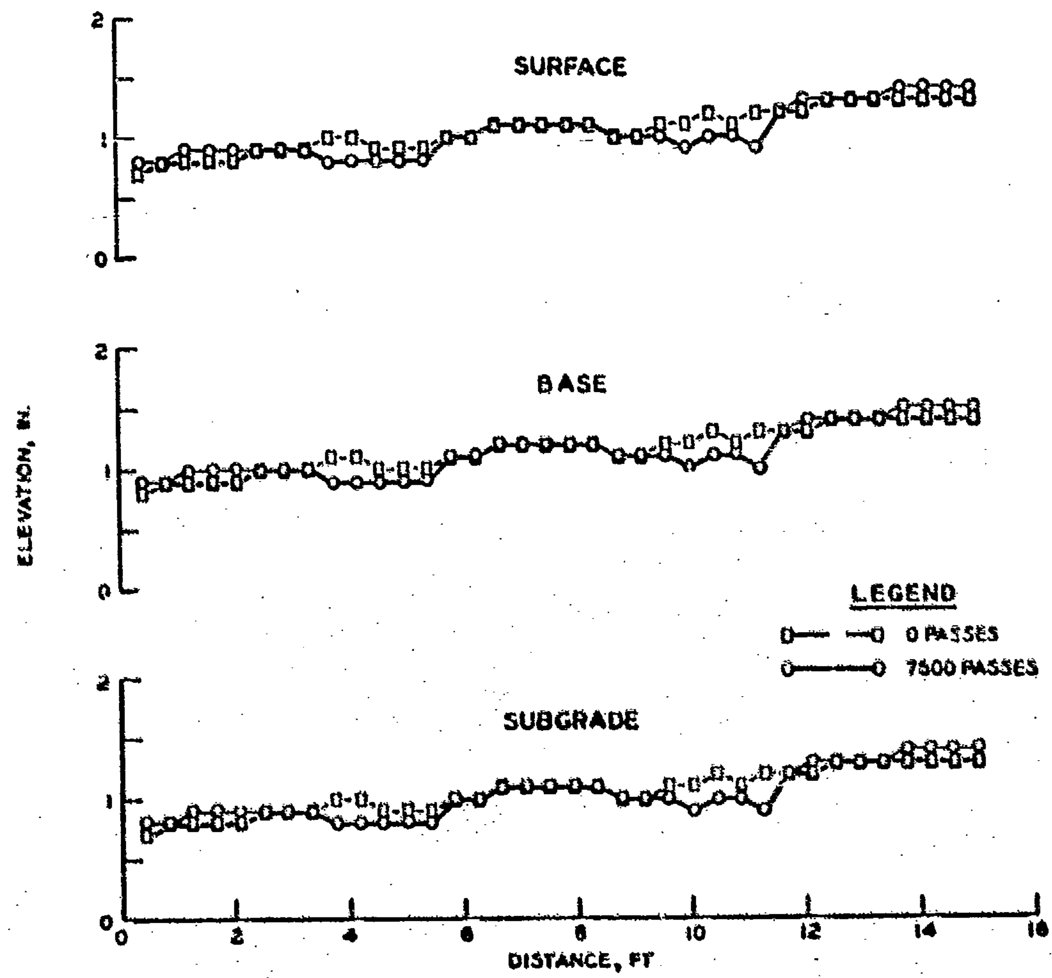

Figure 69. Item 1 - cross section profiles

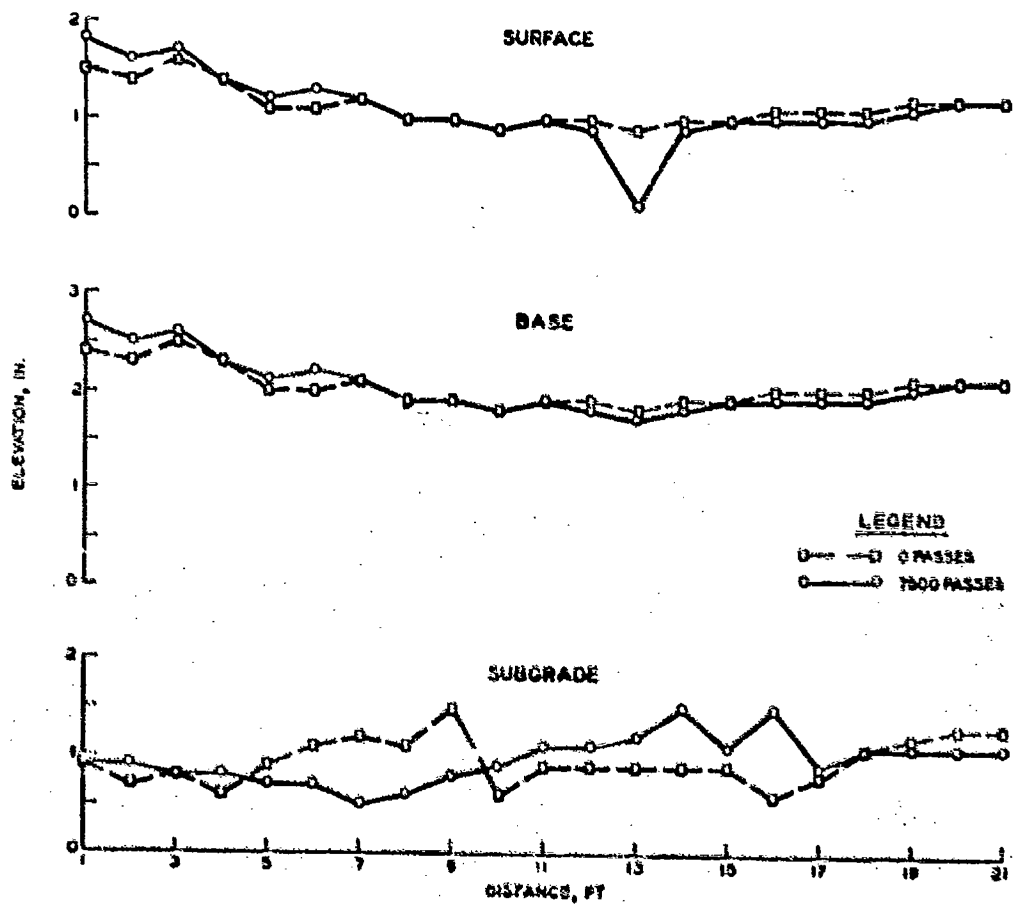

Figure 70. Item 1 - longitudinal profiles, east wheel path

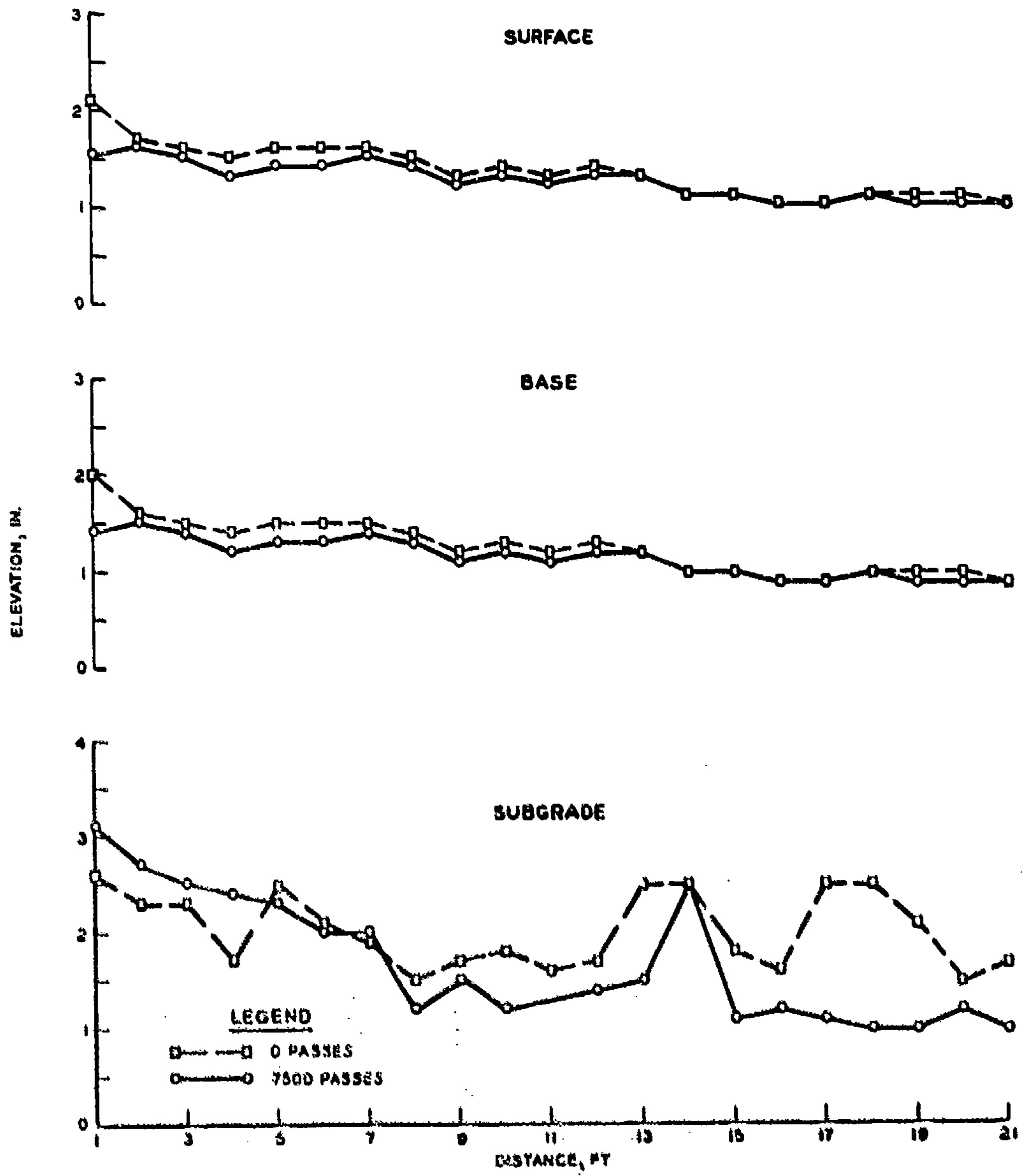

Figure 71. Item 1 - longitudinal profiles, west wheel path

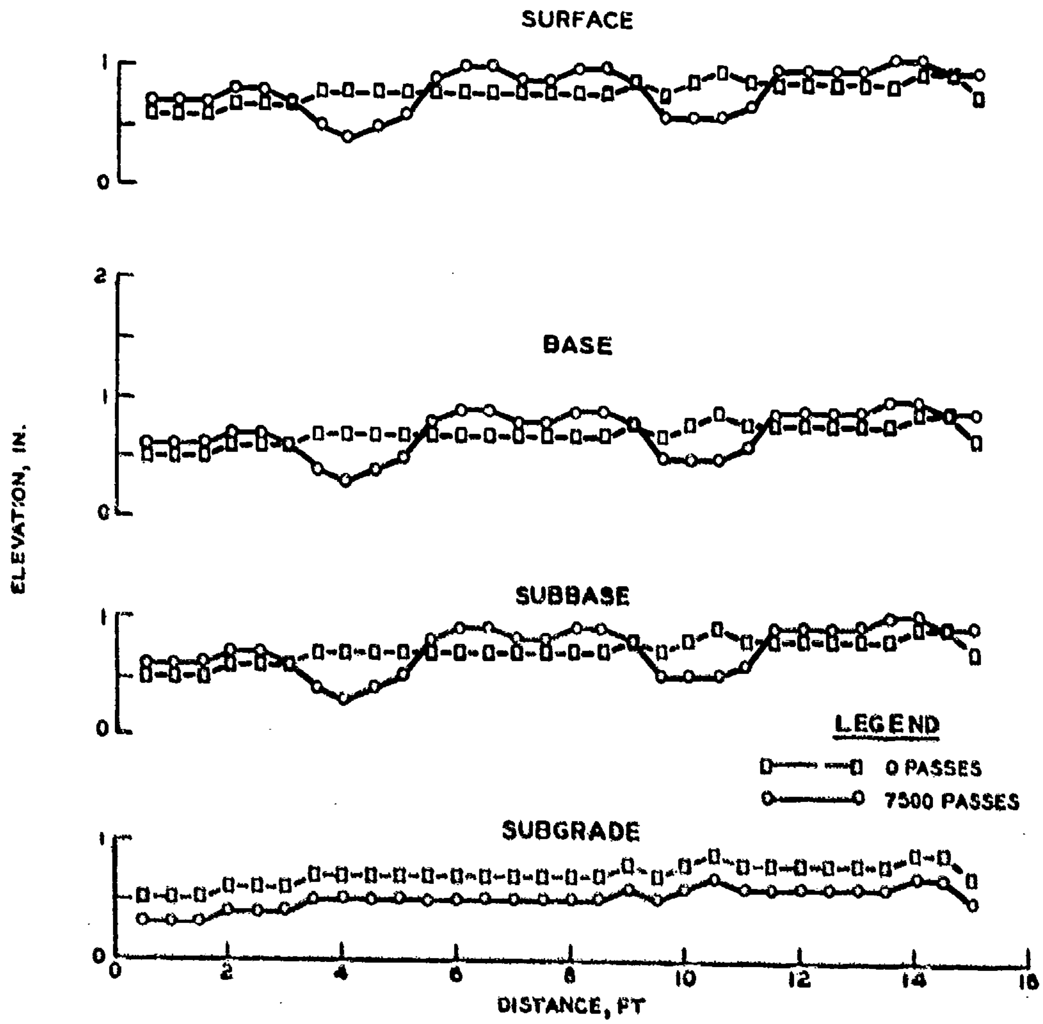

Figure 72. Item 2 - cross section profiles

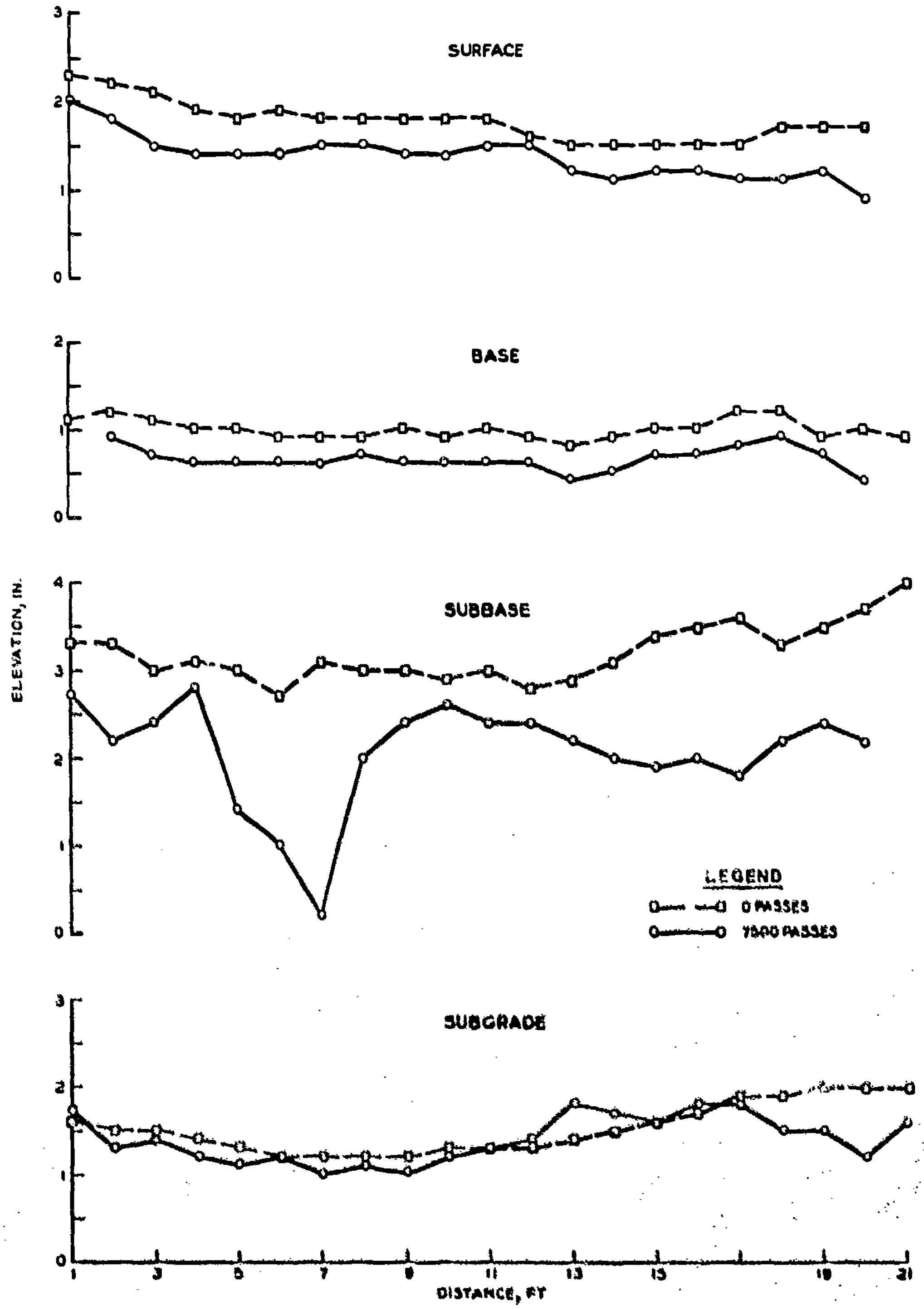

Figure 73. Item 2 - longitudinal profiles, east wheel path

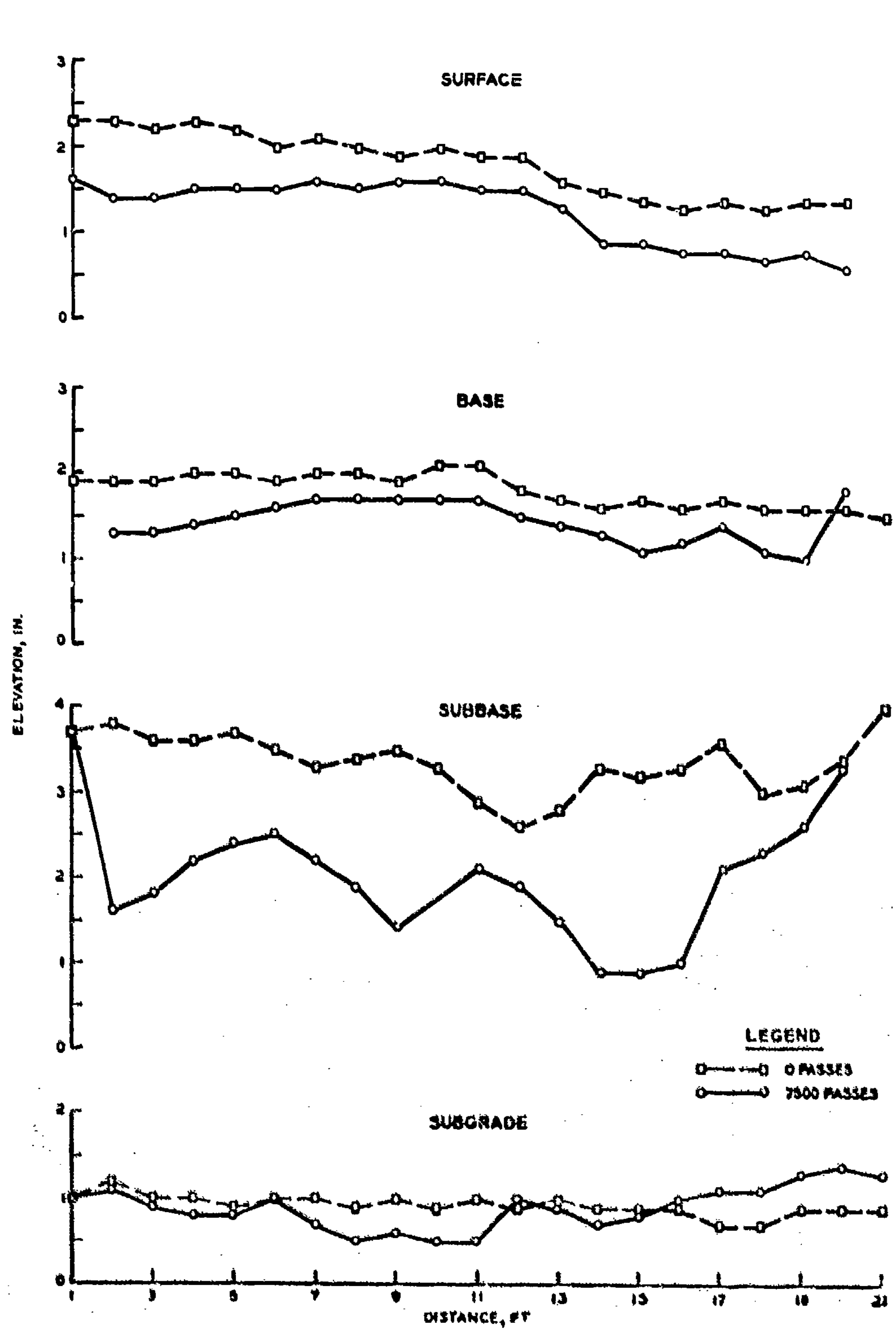

Figure 74. Item 2 - longitudinal profiles, west wheel path

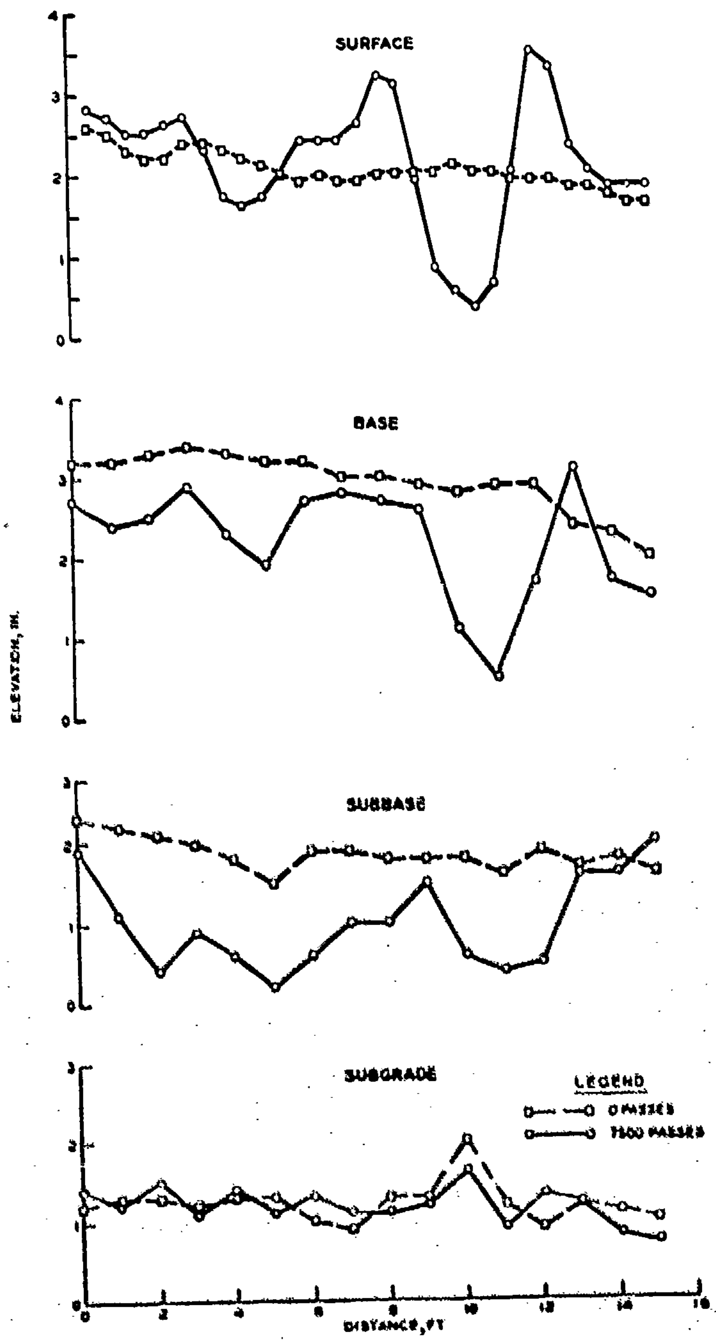

Figure 75. Item 3 - cross section profiles

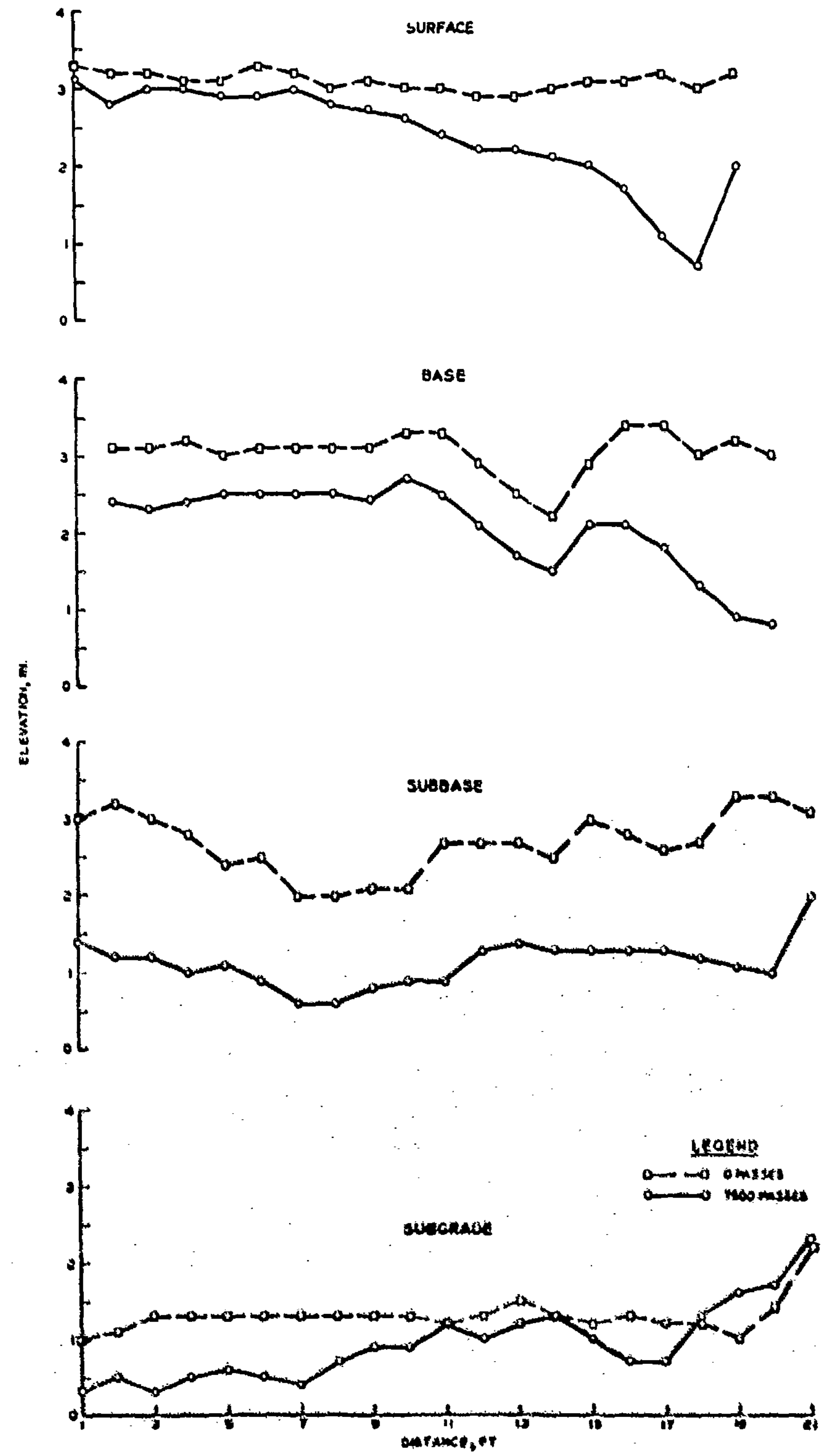

Figure 76. Item 3 - longitudinal profiles, east wheel path

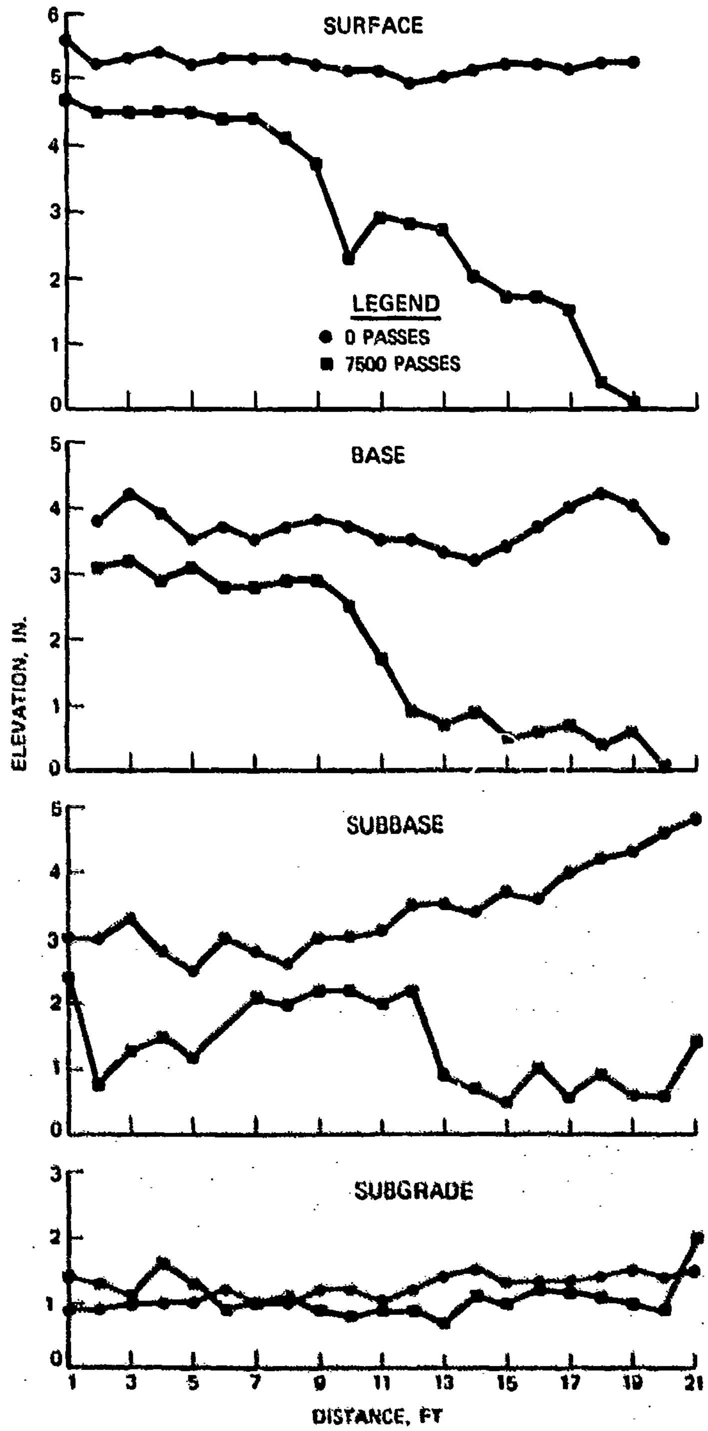

Figure 77. Item 3 - longitudinal profiles, west wheel path

traffic, test pits were dug near the transverse center line, and similar data were recorded inside and outside the trafficked area. A nuclear density gage was used to record wet densities for the crushed stone and gravelly sand, and dry densities were calculated using the moisture content from oven-dried moisture samples. Density measurements for the clay were made using a water balloon testing device. Tables 18 and 19 summarize the results of the density, moisture content, and CBR measurements.

143. At the conclusion of traffic testing, plate load tests were run on the block surface and then on the surface of the base course to determine a modulus of soil reaction (k). The results of these tests are tabulated below.

	k , pci		
Item	On Block Surface	On Base Surface	Block Value ÷ Base Value
1	294	200	1.47
2	182	167	1.09
3	164	123	1.33

Analysis of Results

144. Item 1 gave the best performance of all the items. Figures 69 to 71 show a small general surface subsidence of about 0.2 in. in the trafficked area. There is no sign of any upheaval outside the wheelpath. These profiles, along with the increase in crushed limestone density in Table 18 from 89.4 percent of CE-55 outside the traffic lane to 100.3 percent of CE-55 inside the traffic lane, strongly indicate that the surface change was due to densification in the base.

145. Item 1 with only a 4-in. base was designed as the weakest test item, but the surface of the subgrade dried out to form crust which increased the CBR from the original 3 percent to 6 or 7 percent. CBR measurements taken 6 in. below the clay surface inside and outside the traffic path gave results of 4 percent. Moisture contents in Table 18 also suggest that drying of the buckshot clay subgrade formed a thin crust less than 6 in. thick in item 1.

146. The item 2 profiles in Figures 72 to 74 show a general surface subsidence inside the trafficked area of 0.2 to 0.4 in. with extreme values approaching 0.9 in. The cross sections in Figure 72 show a small but distinct upheaval of 0.1 in. outside the traffic lane. These cross sections also suggest that the gravelly sand was the source of the surface rutting.

147. The crushed limestone in item 2 (Table 18) shows no increase in density between trafficked and untrafficked areas, although there is a large increase in density between the construction and after traffic data. This crushed limestone base never reached densities or CBR values comparable to the base in item 1. The gravelly sand in item 2 showed no change in density between trafficked and untrafficked areas but showed a distinct reduction in density from the construction data. CBR values in Table 18 are very low compared to the design value of 50 from laboratory tests. This is partially due to the difficulty of running a field CBR on a completely cohesionless soil where conditions of confinement and surcharge are much different from the laboratory. Another problem is the low density obtained in the field, which has a direct bearing on the CBR.

148. Item 3 had the poorest performance of all the test items. Rutting in Figure 66 is very pronounced when compared to the other items. The cross sections in Figure 75 show a maximum surface rut 1.4 in. deep and maximum upheaval of 1.3 in. Both the base and subbase show large deformations, but the subgrade shows relatively little deformation. The item 2 comments on the density and CBR values in Table 18 appear valid for item 3 except the crushed limestone base traffic lane density and CBR values showed a sharp increase over those taken outside the traffic lane.

149. The Corps of Engineers designs flexible pavements by requiring that each layer be protected against shear deformation by a specified thickness of material with a higher shear resistance as evaluated by the CBR test. The design curve shown in Figure 78 for 18,000-lb axle loads is the one now used by the Corps of Engineers to select a thickness of required superior material above a given CBR material for road and

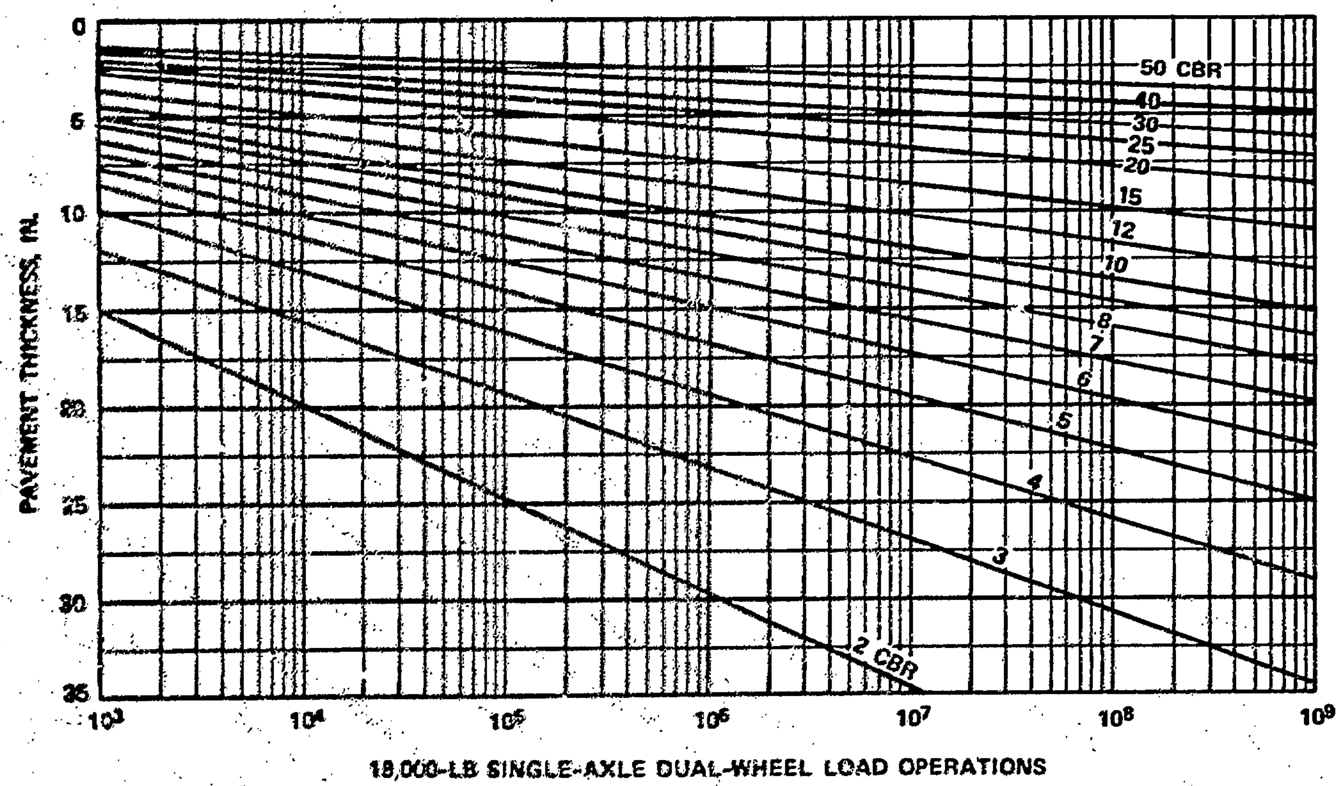

Figure 78. CBR design curve for 18,000-lb single-axle dual-wheel load

street design. CBR design curves protect against a 1-in. shear upheaval above the original surface outside the traffic lane. CBR design provides no protection against densification in the pavement layers. This is handled separately by a compaction requirement that specifies that the field density must reach minimum percent of the optimum CE-55 laboratory density. The required percent of CE-55 density varies with layer depth, loads, and soil type and is available in the Army flexible pavement design manual for roads and streets (Department of the Army 1980).

150. Previous investigators have generally agreed that block pavements behave in manner similar to conventional flexible pavements, and the profile rutting in items 1 to 3 shows that surface rutting is similar to rutting of conventional flexible pavements. The Corps of Engineers current design method for block pavements (Department of the Army 1979) follows the recommendations of Knapton (1976) and replaces the sand and block layer with an equivalent 6.5-in. thickness. Then the block pavement is designed with the resulting equivalent pavement thickness using existing flexible pavement CBR curves.

151. Table 20 compares the actual traffic on the test section with predicted capacity using the CBR design with actual thickness and the equivalent thickness. The predicted operations in Table 20 were developed from Figure 78 which is based on vehicle operations or passes being distributed in an 11-ft-wide lane. To allow comparison on the same basis the actual operations at failure in Table 20 are calculated by multiplying the actual coverage level by a pass to coverage level of 1.13 for an 11-ft-wide lane as recommended by Brown and Ahlvin (1961) and as used in Figure 78. The crushed limestone bases were analyzed with a CBR value of 100 percent, consistent with its laboratory test results discussed earlier. The field test results in Table 18 show density and CBR remaining the same or increasing from construction data outside of traffic to the inside of traffic lane. In item 1, the base did reach a 100 percent CBR value. These data all confirm that the crushed limestone field performance agreed with the laboratory prediction. Although the gravelly sand subbase meets the laboratory requirements for a 50 percent CBR subbase, its field performance proved unsatisfactory. All

cohesionless materials depend on confining stresses to develop shear strength, and this particular gravelly sand has given unsatisfactory subbase performance before when covered by relatively thin base and surfacing (e.g., Ahlvin et al. 1971). The thin base, sand, and block layers apparently did not provide sufficient confinement for the gravelly sand subbase. The shear failure in the subbase is clearly visible in the thinning of the subbase along the longitudinal profile in Figures 73, 74, 76, and 77, and the upheaval is visible in the cross section in Figures 72 and 75. The decrease in density from the values of the construction data in Table 18 to the values for the outside of traffic and in traffic tests also suggests shearing occurred in the subbase material. The subbase was given a design CBR of 20 percent for Table 20, which is the lowest design CBR value normally allowed for subbase materials. Design CBR values for the clay were selected from the in traffic values in Table 18.

152. Items 1 and 2 never approached the failure condition of 1-in. upheaval outside the traffic lane, but item 3 reached this condition after 5400 passes (5140 coverages or 5808 operations in Table 20). An examination of Table 20 shows that predictions using the CBR design, either with actual thickness or with equivalent thickness, did not anticipate actual performance accurately. Without the use of the equivalent thickness approximation the CBR design method is very conservative. For all cases of predicted performance the clay layer is critical, but under actual traffic the clay never showed any sign of significant shearing. Failure of item 3 was due to the failure in shear of the subbase, which is not adequately represented by the reduction of the CBR to 20 percent. An appreciably lower number is necessary, but the effective CBR cannot be determined from the traffic tests because the actual effect of the block surface is unknown.

153. Under similar traffic conditions the 3.1-in.-thick block in item 2 did much better than the 2.4-in.-thick block in item 3. The shaped blocks in items 1 and 3 gave much higher ratios of the k on the block surface to the k on the base course (tabulated in paragraph 143) than on the rectangular block in item 2. This suggests some

advantage in load distribution characteristics for shaped blocks when compared to rectangular block. However, under traffic the advantage of the thicker block in item 2 outweighed any advantage of the block shape in item 3.

Conclusions

154. The following conclusions can be made:

   a. Block pavements behave in a manner similar to flexible pavements.

   b. Block pavements can be designed and constructed to carry heavy truck traffic over a soft clay subgrade.

   c. The 6.5-in. equivalency adopted by the Corps of Engineers (Department of the Army 1979) for block pavement design will allow a conservative design but will not predict actual performance.

   d. Limited data suggest that increased block thickness can outweigh improved load distributing characteristics of shaped blocks.

PART VII: ANALYSIS AND DESIGN

Behavior

155. A concrete block pavement functions as a flexible pavement. Loads applied to the high-quality block surface are distributed through progressively lower quality materials to the subgrade. Both interlocking and rectangular blocks effectively distribute load to lower layers, as shown in Figure 23. The plate load tests tabulated in paragraph 143 also indicate that the block surface has load-distributing capability and extensive pressure cell measurements under shaped blocks reported by Shackel (1978) provide further confirmation. The block test section rutting described in Parts V and VI of this report are consistent with flexible pavement behavior.

156. Although the block pavement behaves as a flexible pavement in general terms, there are significant differences between an asphaltic concrete surfaced flexible pavement and a concrete block surfaced flexible pavement. In a multilayered elastic system the load-distributing characteristics of any layer increases as the elastic modulus of the layer increases. However, in the case of a thin surface layer with a much higher modulus than the next lower layer (thin concrete over a thick granular base, for instance) the maximum horizontal shear stresses at the middle of the stiff layer and tensile stresses at the bottom of the layer increase significantly (Yoder and Witczak 1975). This distribution of stresses is quite different from a conventional asphaltic concrete flexible pavement.

157. The block layer is not an elastic layer, but consists of modular units separated by sand-filled joints. Consequently, the load-distributing characteristics and stress levels in the blocks themselves cannot be calculated with elastic theory. Pressure cell measurements by Shackel (1978) showed some indications that pressure measurements under the block surface decreased with load applications. This may indicate that an increase in the stiffness or load-distributing ability of the block layer occurs as the blocks wedge more tightly together or interlock under traffic.

158. Block pavements distribute loads in a manner similar to conventional flexible pavements, but their modular nature makes it exceedingly difficult to evaluate them analytically. Several investigators have attempted to reduce the block surface to an equivalent thickness of conventional flexible pavement material for design. Although block pavements are a flexible pavement, their modular nature, individually high block elastic modulus values, and possible increasing stiffness under traffic make them significantly different from conventional asphaltic concrete flexible pavements.

Block Shape and Laying Pattern

159. The plate load tests conducted by Knapton (1976) and Clark (1978) found no difference in the load-distributing ability of rectangular and shaped blocks. These test results are shown in Figure 24, and Lilley (1980) states that block pavement performance in the United Kingdom since their tests confirm these results. Shackel (1979, 1980) concluded from his trafficking tests in Australia and South Africa that shaped blocks that interlock perform better than rectangular blocks. However, the large range of subgrade CBR values in Table 16 requires additional experimental data to confirm this conclusion.

160. In the WES trafficking test (Part VI) rectangular blocks performed well, and in the Netherlands rectangular blocks have a long history of acceptable use (Kellersmann 1980, Van der Vlist 1980). In Table 14, items 4 and 7 and items 5 and 6 differed only in block shape, but there was little difference in their deformation under traffic. The information that is available now indicates that either rectangular or interlocking shaped blocks can be used in pavements, and no difference in performance has been proven.

161. The most common laying patterns for block pavements subject to vehicular traffic are either herringbone or stretcher bond (see Figure 3). Shackel (1980) found in trafficking tests that there was some indication that herringbone laying patterns outperformed stretcher bond, but he felt more experimental data were needed to confirm this. Lilley

and Collins (1976), Lilley and Clark (1978), and Lilley and Walker (1978) only recommended using the stretcher bond and herringbone laying patterns under vehicular traffic. Also, based on observations of block pavements in the Netherlands and in a car park in the United Kingdom, Lilley (1980) recommended that rectangular blocks subject to vehicular traffic should always be laid in a herringbone pattern to avoid creep. This creep displaces the rectangular blocks laid in stretcher bond in the direction of traffic. With the information now available it appears that rectangular blocks subject to traffic should be laid in a herringbone pattern, while interlocking shaped blocks may be placed in either herringbone or stretcher bond patterns.

Block Thickness

162. The plate load test results in Figure 24 from Clark (1978) show that as the paving block thickness increases the load spreading ability of the paving block surface increases. However, the effect in this figure is modest and there is a significant amount of scatter in the data. Knapton (1976) did not feel that the effect of block thickness could be quantified and recommended use of the 3.1-in.- (80-mm-) thick block for all but the most lightly trafficked pavement. This recommendation was based on the experience and recommendation of continental Europe.

163. On the basis of traffic tests on the high-strength Australian test subgrade, Shackel (1980b) concluded that block thickness was a major design factor. Block thickness affected rutting, surface deflections, and subgrade stresses. The WES traffic test also showed markedly improved performance of the 3.1-in.-thick block in item 2 over the 2.4-in.-thick block in item 3 with similar support conditions.

164. Block thickness has been shown to have a decided effect on block pavement performance in the United Kingdom plate load tests, the Australian road simulator tests, and the WES trafficking tests. However, the only method developed to analytically evaluate the effect of block thickness is Shackel's (1978) regression equations, which as

discussed earlier cannot be safely extrapolated to conditions different from the Australian road simulator test pavement.

Laying Course

165. The sand laying course of 1 to 2 in. used underneath the paving blocks is a construction necessity to allow the final leveling of the block surface, but it is an element of structural weakness in the pavement. Although Shackel (1979) found that a sand laying course contributed to the reduction of stress in the underlying layers, Figure 36 (Shackel 1978) and the tabulation in paragraph 101 (Seddon 1980) clearly show that the sand layer as presently constructed densifies under traffic. This has to result in a deterioration of the smoothness of the pavement surface.

166. To avoid or at least minimize this, the sand layer thickness should be kept to a minimum. The recommendations of Shackel (1978) and their successful application in the WES traffic tests indicate that the thickness of the sand laying course should be limited to 1 in. If this sand layer is properly compacted, an improved surface must result. Either the sand layer can be compacted better prior to placement of the blocks with acceptance of the problems noted by Lilley (1980), summarized in paragraph 42, or else the paving blocks can be compacted with heavier and more effective vibratory compaction equipment to limit densification of the sand under traffic. Tests must be conducted to determine the effectiveness of these suggestions.

Design

167. Initial design methods for block pavements were developed from continental European experience. These designs were essentially qualitative and specified base and block thicknesses that had previously proved adequate for similar subgrades, traffic, and climates. When block pavements began to spread to areas without continental Europe's experience with block pavements, users began to demand design methods

that could be used with confidence in these new areas. Also, as blocks began to be used for road and storage areas subject to heavy traffic loads over poor subgrades, the need for improved paving block design methods became apparent. A design method for block pavements should provide a safe, economical pavement and must account for variations in subgrade strength and traffic loadings.

168. Block pavements generally fail by rutting, and individual block breakage has been a minor, isolated distress. The high-quality blocks now in use have proven adequate to withstand the stresses generated by a variety of heavy loads. The block surface distributes the applied load over a larger area which reduces the stresses on the lower pavement layers. Rutting in block pavement is caused by densification or shear deformation in the underlying base, subbase, and subgrade. The allowable rutting in a pavement can vary, depending on the use of the surface and desires of the user.

169. Densification can be controlled by requiring adequate compaction in the pavement layers and existing flexible pavement criteria found in current design manuals (Department of Defense 1978, Department of the Army 1980) should be adequate. Protection against shear is a more complex problem since block surfaces distribute load over a larger area than asphaltic concrete surface. Consequently, existing flexible pavement design based on experience with asphaltic concrete will be conservative. Figure 79 compares failure data extracted from Figure 25 and Table 16. From Figure 25, failure was taken as 1-in. vertical deformation, and in Table 16 only data from the first trafficking of a section was considered. Figure 79 also contains data from the WES tests in Figure 23 and the Australian tests summarized in the tabulation in paragraph 106, and these data were all plotted as not failing since rutting was either much less than 1 in. or occurred due to a weakness in a pavement layer above the subgrade. The data from Seddon (1980) were not used because the strength of the subgrade was unknown. The data from Barber and Knapton (1980) were not used since deformation contributions from the subgrade and poor quality base could not be separated.

170. From Figure 79, it appears that a separating line between

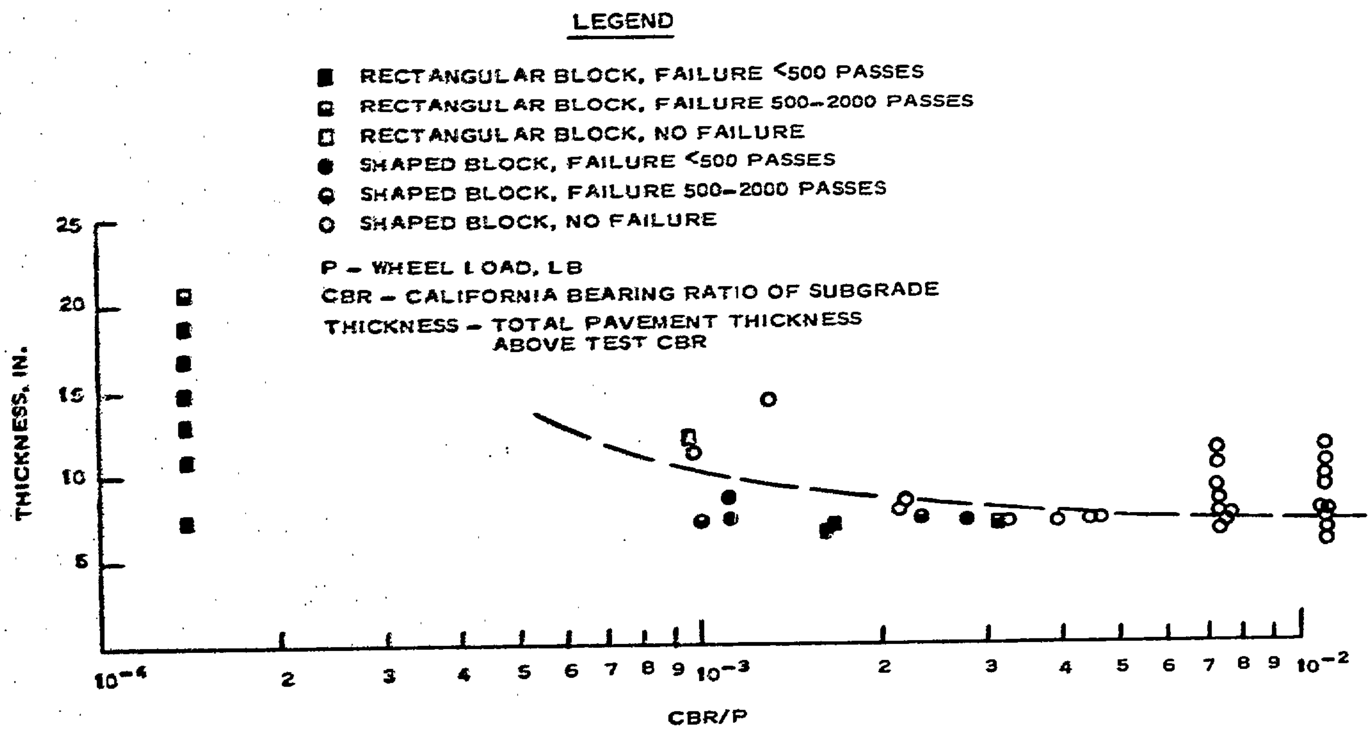

Figure 79. Failure of test items with varying thickness, CBR, and wheel loads

failure and nonfailure for 500 passes could be estimated, but there is a significant gap in the data. The data also show that rectangular block test results are clustered to the left of the diagram, indicating severe test conditions of low CBR or high wheel loads, while shaped block test results are clustered to the right of the diagram, indicating less severe test conditions. This further illustrates why claims that shaped blocks outperform rectangular blocks cannot be accepted from the test data presently available. The minimum thickness for a block pavement will be about 7.4 in.: 4-in. base, 1-in. sand leveling course, and 2.4-in. block. More test results are needed to fill in the gaps in the existing test section data before more extensive analysis can be expected to provide a separate empirical design for block pavements or an empirical adjustment to existing flexible pavement design.

171. Selection of a design method for block pavements is mainly limited to methods based on previous experience, Shackel's (1980b) proposed method based on regression equations (Shackel 1978) developed from field tests, the National Concrete Masonry Association (1980) method that uses conventional CBR flexible pavement relationships, or the modified CBR flexible pavement design method that allows increased effective or equivalent thickness for the paving block and sand laying course (Knapton 1976, Department of the Army 1979). The design methods that rely on previous experience with similar subgrades, pavement materials, traffic, and climate cannot be used unless all of these conditions are duplicated at the new site. The experience-based methods also tend to be conservative and are probably most appropriate for lightly loaded pavements in areas with previous experience with block pavements. As discussed in Part V, Shackel's regression equations cannot be applied to protect against shear deformation or for conditions different from the Australian test track conditions. Consequently, their use cannot be justified for design. The direct adoption of conventional CBR flexible pavement design curves fails to give any weight to the increased load-distributing ability of the paving blocks. The use of an equivalent increased thickness with CBR design curves as originally proposed by Knapton (1976) and later adopted by the Corps of Engineers (Department of

the Army 1979) offers a useful design expedient that recognizes the increased load-distributing ability of the paving blocks. However, the existing equivalent thickness that is used is based on simplifying assumptions and limited testing that could be improved. With the information currently available, the existing modified CBR flexible pavement design methods using an equivalent thickness appear to be the most practical. The recommended design method consists of first developing a conventional flexible pavement design using the Corps of Engineers CBR method and then treating the sand and concrete paving block as equivalent to 6-1/2 in. of asphalt concrete surfacing and base material. This will provide a conservative design but cannot be expected to predict actual performance.

172. Shackel (1980b) has proposed a design method for paving block on stabilized material by using elastic layer analysis. There are no data presently available that will allow evaluation of these conditions. Until more data are developed, the established Corps of Engineers equivalency factor for stabilized materials (Department of Defense 1978, Department of the Army 1980) can be used to conservatively design paving block pavements with stabilized layers. Design for frost conditions should use the current Corps of Engineers flexible pavement methods (Department of the Army 1965), but actual thicknesses instead of equivalent thicknesses should be used for calculating frost protection.

Block Strength

173. Block breakage has not been a major cause of block pavement distress even though Seddon (1980) has trafficked blocks with compressive strengths as low as 5420 psi, and Shackel (1979) has used blocks as low as 3700 psi. This suggests that the block strength requirements in Table 2 are conservative for traffic loads, but these high strengths may be needed for handling and abrasion resistance. If lower strengths are achieved through reduced cement contents, the consequent increase in the water-cement ratio will tend to produce a concrete of greater permeability which will allow critical saturation to develop faster when

the product is exposed to water. This concrete will be more susceptible to freezing and thawing damage unless it is protected by an adequate pore structure such as provided by proper air entrainment. These factors must be studied in more detail before lower strengths for these products can be accepted.

PART VIII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

174. The following conclusions are made:

a. Concrete paving blocks are a proven pavement material capable of providing an aesthetic surface that can support heavy loads over soft subgrades, requires comparatively little maintenance, and allows easy access to utilities or similar items below the pavement surface. Concrete paving block can only be used for low-speed traffic. They have a high initial cost and low maintenance cost.

b. Current Corps of Engineers method of design (Department of the Army 1979) using an equivalent thickness appears to be the most practical method of achieving a conservative design but will not accurately predict actual block pavement performance.

c. Either rectangular or shaped interlocking blocks can be used for pavements, but rectangular blocks subject to vehicular traffic should only be laid in a herringbone pattern while shaped interlocking blocks can be placed in either a herringbone or stretcher bond pattern.

d. Specifications for paving blocks should include the following:

(1) Strength. Blocks with a compressive strength of approximately 8000 psi have a proven history of performance.

(2) Resistance to freezing and thawing. Either a proven history of performance under similar site conditions or a laboratory freeze-thaw test should be required.

(3) Dimensional tolerance. Standard of the local industry such as National Concrete Masonry Association (1979) in the U. S. or DIN 18501 in Germany should be used.

(4) Abrasion resistance. A modified sandblast test or other abrasion test method should be developed to test for thin, defective surfaces on the block.

Recommendations

175. The following recommendations are made:

a. Additional trafficking tests and analysis of existing

pavements are needed to develop a more accurate and less conservative design procedure. Development of an improved procedure by the Corps of Engineers does not appear warranted unless use of block pavements by the Corps increases considerably.

b. The effects of using lower strength blocks is worth further study and field trials.

c. Construction procedures to automate block placement and to improve compaction of the sand bedding layer should be investigated.

d. Methods of reducing initial block pavement permeability should be developed.

REFERENCES

Ahlvin, R. G. et al. 1971. "Multiple-Wheel Heavy Gear Load Pavement Tests," Technical Report S-71-17, 5 Vol, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

American Concrete Institute. 1969. "Recommended Practice for Concrete Floor and Slab Construction," ACI 302-69, Detroit, Mich.

Asphalt Institute. 1979. "Chicago's State Street Is Now an Asphalt-Paved Transit Mall," Asphalt News, Vol 2, No. 4, College Park, Md.

Australian Road Research Board. 1981. "Concrete Block Test Pavement Installed at ARRB," Australian Road Research, Vol 11, No. 1, Vermont, Australia.

Barber, S. D., and Knapton, J. 1980. "An Experimental Investigation of the Behavior of a Concrete Block Pavement with a Sand Sub-Base," Proceedings, Institute of Civil Engineers, Part 2, Vol 69, 1 March, pp 139-154.

Besser Company. (No date). "The Besser Company Paving Stone Manual," Alpena, Mich.

Brown, D. H., and Ahlvin, R. G. 1961. "Revised Method of Thickness Design for Flexible Highway Pavements at Military Installations," Technical Report No. 3-582, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Cedergren, H. R. 1974. Drainage of Highway and Airfield Pavements, John Wiley and Sons, New York.

Cement and Concrete Association. 1976. "Continental Experience Shows Growth Potential for Interlocking Paving," Precast Concrete, Vol 7, No. 6, United Kingdom, pp 297-298.

Cement and Concrete Association. 1978. "Concrete Block Paving, Model Specifications Subject to Adaption," Wexham Springs, United Kingdom.

Clark, A. J. 1978. "Block Paving Research and Development," Concrete, Vol 12, No. 7, Cement and Concrete Association, United Kingdom, pp 24-25.

Clark, A. J. 1979. "Water Penetration Through Newly Laid Concrete Block Paving," Technical Report 529, Cement and Concrete Association, Wexham Springs, United Kingdom.

Clark, A. J. 1980. "Freeze-Thaw Durability Tests Upon Concrete Paving Block Specimens," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Cruickshank, J. W. 1976. "Interim Guide to the Design and Construction of Interlocking Sett Pavements," Technical Note 32, Cement and Concrete Association, Australia.

Dawson, A. J. 1980. "Mix Design for Concrete Block Paving," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Department of the Army. 1965. "Pavement Designs for Frost Conditions," Technical Manual 5-818-2, Washington, D. C.

Department of the Army. 1971. "Flexible Pavements for Roads, Streets, Walks and Open Storage Areas," TM 5-822-5/AFM 88-7, Chapter 3, Washington, D. C.

Department of the Army. 1975. "Standard Practice for Concrete Pavements," TM 5-822-7/AFM 88-6, Chapter 8, Washington, D. C.

Department of the Army. 1979. "Use of Precast Concrete Block Pavements," ETL 1110-3-310, Office, Chief of Engineers, Washington, D. C.

Department of the Army. 1980. "Engineering and Design, Flexible Pavements for Roads, Streets, Walks, and Open Storage Areas," TM 5-827-5/AFM 88-7, Chapter 3, Washington, D. C.

Department of Defense. 1978. "Flexible Pavement Design for Airfields," TM 5-825-2/DM 21.3/AFM 88-6, Chapter 2, Washington, D. C.

Dreijer, P. A. 1980. "Laboratory and Fieldwork on Block Paving," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Federal Highway Administration. 1980. "Highway Subdrainage Design," Report No. FHWA-75-80-224, Washington, D. C.

Gerrard, J. S. 1980. "Review of Block Paving in United Kingdom Ports," First International Conference on Concrete Block Pavements, University of Newcastle-Upon-Tyne, England.

Harris, D. 1978. "An Examination of the Use of Concrete Paving Blocks as a Pavement Surfacing Course," Report No. 78/22, Main Roads Department of Western Australia, Materials Engineering Division, Australia.

Hodgkinson, J. A., and Morrish, C. F. 1980. "Interim Guide to the Design of Interlocking Concrete Pavements for Vehicular Traffic," TN 34, Cement and Concrete Association, Australia.

Kellersmann, G. H. 1980. "Urban Block Paving in the Netherlands," First International Conference on Concrete Block Pavements, University of Newcastle-Upon-Tyne, England.

Knapton, J. 1976. "The Design of Concrete Block Roads," Report No. 42.515, Cement and Concrete Association, Wexham Springs, United Kingdom.

Knapton, J., and Barber, S. D. 1979. "The Behavior of a Concrete Block Pavement," Proceedings, Institute of Civil Engineers, Part 1, Vol 66 pp 277-292.

Knapton, J., and Barber, S. D. 1980. "U. K. Research into Concrete Block Pavement Design," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Knapton, J., and Lilley, A. A. 1975. "A Study Visit to Germany and Denmark," Cement and Concrete Association, Wexham Springs, United Kingdom.

Kuthe, Ernst-Otto. 1980. "Concrete Paving Block Today," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Lane, R. O. 1978. "Abrasion Resistance," Chapter 22, Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM Special Technical Publication 69B, American Society for Testing and Materials, Philadelphia, Pa.

Lesko, S. 1980. "The Use of Concrete Block Pavements for Highways," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Litvan, G. and Sereda, P. 1978. "Particulate Admixtures for Enhanced Freeze-Thaw Resistance of Concrete," Cement and Concrete Research, Vol 18, No. 1, pp 53-60.

Lilley, A. A. 1980. "A Review of Concrete Block Paving in the U. K. Over the Last Five Years," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Lilley, A. A., and Clark, A. J. 1978. "Concrete Block Paving for Lightly Trafficked Roads and Paved Streets," Report No. 46.024, Cement and Concrete Association, Wexham Springs, United Kingdom.

Lilley, A. A., and Collins, J. R. 1976. "Laying Concrete Block Paving," Report No. 46.022, Cement and Concrete Association, Wexham Springs, United Kingdom.

Lilley, A. A., and Walker, B. J. 1978. "Concrete Block Paving for Heavily Trafficked Roads and Paved Areas," Technical Report 46.023, Cement and Concrete Association, Wexham Springs, United Kingdom.

Mather, B. 1975. "Durability of Concrete Construction--50 Years of Progress," Vol 101, No. CO1, Journal of the Construction Division, American Society of Civil Engineers, New York, pp 5-14.

Meyer, A. 1980. "Materials and Specifications in West Germany," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Miller-Cook, D. 1980. "Concrete Block Paving - Survey of Industrial Applications in the U. K.," First International Conference on Concrete Block Pavements, University of Newcastle-Upon-Tyne, England.

Morrish, C. F. 1980. "Interlocking Concrete Paving - The-State-of-the-Art in Australia," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

National Concrete Masonry Association. 1979. "Concrete Block Pavements Design and Construction," Herndon, Va.

National Concrete Masonry Association. 1980. "Concrete Block Pavements Structural Design," TEK 115, Herndon, Va.

Nettles, E. H., and Calhoun, C. C. 1967. "Drainage Characteristics of Base Course Materials Laboratory Investigations," Technical Report No. 3-786, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Neville, A. M. 1973. Properties of Concrete, 2d ed., John Wiley and Sons, New York.

Ozyildirim, C., and Sprinkel, M. 1982. "Durability of Concrete Containing Hollow Plastic Microspheres," MS 5161, American Concrete Institute.

Patterson, W. D. O. 1976. "Functional Pavement Design for Container Terminals," Proceedings, The Eighth Australian Road Research Board Conference, Vol 8, Part 4, Perth, Australia, pp 22-29.

Pesch, L. 1980. "Concrete Paving Blocks in Industrial Construction in West Germany," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Powers, T. C. 1975. "Freezing Effects in Concrete," SP 47-1, Durability of Concrete, American Concrete Institute, Detroit, Mich.

Precast Concrete. 1979. "Uniblocks at Port Rashid," Vol 10, No. 12 (Dec), United Kingdom, pp 5-84.

Seddon, P. A. 1980. "The Behavior of Concrete Block Paving Under Repetitive Loading," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Shackel, B. 1978. "An Experimental Investigation of the Response of Interlocking Concrete Block Pavements to Simulated Traffic Loading," Seminar on Interlocking Concrete Block Pavements, Australian Road Research Board, Australia.

Shackel, B. 1979. "A Pilot Study of the Performance of Block Paving Under Traffic Using a Heavy Vehicle Simulator," Proceedings, Symposium on Precast Concrete Paving Blocks, Johannesburg, South Africa.

Shackel, B. 1980a. "The Performance of Interlocking Block Pavements Under Accelerated Trafficking," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Shackel, B. 1980b. "The Design of Interlocking Concrete Block Pavements for Road Traffic," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Shackel, B., and Arora, M. G. 1978a. "The Evaluation of Interlocking Block Pavements," An Interim Report, Proceedings, Annual Conference, Concrete Masonry Association, Australia.

Shackel, B., and Arora, M. G. 1978b. "The Application of a Full-Scale Road Simulator to the Study of Highway Pavements," Australian Road Research, Vol 8, No. 2, June.

Sharp, K. B. 1980. "An Initial Study into Concrete Block Paving," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Spears, R. E. 1978. "Concrete Floors on Ground," Portland Cement Association, Skokie, Ill.

Van der Vlist, A. A. 1980. "The Development of Concrete Paving Blocks in the Netherlands," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Van Leeuwen, H. 1980. "Use of Block Paving in European Ports," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Von Szadkowski, G. 1980. "The Effect of Pigments on the Quality of Concrete Blocks," First International Conference on Concrete Block Paving, University of Newcastle-Upon-Tyne, England.

Wiley, C. C. 1919. "Modern Pavements (A Discussion on Various Types of Pavements, Their Relative Merits and Comparisons with Concrete Roads)," Brick and Clay Record.

Working Committee on Concrete Block Paving. 1965. "Code of Practice for the Construction of Concrete Block Paving," Forschangsgellschaft fur das Strassenwesen (Road Research Association), Germany.

Yoder, E. J., and Witczak, M. W. 1975. Principles of Pavement Design, 2d ed., John Wiley and Sons, New York.

Table 1

West German Use of Paving Block in 1972*

Roads	36.4 percent
Industrial Areas	29.1 percent
Private Drives	12.5 percent
Pedestrian Ways	12.0 percent
Parks, Schools, etc.	6.8 percent
Other	3.2 percent

* From Cement and Concrete Association (1976).

Table 2

Comparison of Paving Block Strength Requirements

	Type of Test	Required Strength, psi
U. S. National Concrete Masonry Association		
Area subject to freeze-thaw cycles	Compressive	8000
Area not subject to freeze-thaw cycles	Compressive	6000
United Kingdom Cement and Concrete Association	Compressive	7250
Netherlands NEN 7000	Flexural	855
German DIN 18501	Compressive	8700

Table 3

Estimated Concrete Block Pavement Construction Output

Source	Estimated Output yd^2/man day
Lilley and Clark (1978)	30 to 60
D. G. Frandsen (1978)*	20 to 30
Morrish (1980)	29.9
Kellersmann (1980)	59.8 to 167

* Personal communication, 1978, Mr. D. G. Frandsen, U. S. Army Engineer Division, Europe, Frankfurt, Germany.

Table 4

Recommended Pavements for Container Terminals (Patterson 1976)

	Loading Category				
Anticipated Settlement	Tractor-Trailer, 38-Kip Axle Load	8-Wheel Carrier, 25.8-Kip Wheel Load	6-Wheel Carrier, 33.7-Kip Wheel Load	4-Wheel Carrier, 41.6-Kip Wheel Load	Anticipated Future Load, 89.9-Kip Wheel Load
Negligible	Asphalt Tar Concrete	Tar Block Concrete	Concrete Tar	Concrete	Concrete
Less than 6 inches	Asphalt Tar Concrete	Tar Block Concrete	Concrete Tar	Concrete Stage	Stage Concrete
More than 6 inches (rapid)	Stage Block Precast	Stage Block Precast	Stage Block Precast	Stage Precast	Stage Precast
More than 6 inches (slow)	Block Precast	Block Precast	Block Precast	Precast	Precast

NOTE: Listed in order of decreasing preference in each category.

Table 5

Cost for Paving Block in Place

Year	Location	Project Size, ft^2	Cost, $\$/ft^2$	Source
1976	Fulda Barracks, Germany	29,900	1.14	Personal communication, Mr. Frandsen, Corps of Engineers
1977	El Cerrito, Calif.	9,280	3.00-3.50	Personal communication, LTC Delano, Corps of Engineers
1978	Perth, Australia	--	1.24	Harris (1978)
	Dover, United Kingdom	290,000	1.17-1.54	Gerrard (1980)
1979	Eastern U. S.	--	1.85-3.00	Personal communication
	California	--	3.00-5.50	Personal communication
1980	Netherlands	--	1.39	Van Leeuwen (1980)

Table 6

Nominal Currency Exchange Rates

Nation	Currency	Exchange Rate, U. S. Dollars			
		1976	1977	1978	1979
Australia	Dollar	--	1.10	1.1565	1.1295
Netherlands	Guilder	--	0.408	0.4592	0.4982
United Kingdom	Pound	--	1.72	1.9325	2.261
West Germany	Mark	0.4265	0.424	0.4984	0.5468

Table 7

Variation in 1978 Bids, Dover, U. K. (After Gerrard (1980))

Bidder No.	Cost for 9.8-in. Lean Concrete $/ft^2*	Cost for 80 mm Block $/ft^2	Total Cost $/ft^2
1	0.78	1.17	1.95
2	1.44	1.54	2.98
3	1.10	1.48	2.58
4	1.00	1.22	2.22
5	0.85	1.54	2.39
6	0.91	1.44	2.35
Mean	1.01	1.40	2.41
Coefficient of Variation**	0.24	0.12	0.14

* Dollars are U. S. dollars.
** Coefficient of variation = Standard deviation ÷ mean.

Table 8

Initial Construction Costs for Comparable Pavements, U. S. Dollars/ft^2

Country	Year	Application	Block	Asphalt	Spray Seal	Concrete	Reference
Australia	1978	Road	1.24	0.28-0.41	0.23	--	Harris (1978)
United Kingdom	1980	Port	4.28	4.36	--	4.85	Gerrard (1980)
Netherlands	1980	Port	2.55	2.55	--	3.70	Van Leeuwen (1980)

Table 9

Traffic Damage to Block Roads

Annual Damage	On Marshy Soil	On Sandy Soil
Depressions in ft^2 per mile of road	107.6	64.6
Broken blocks in ft^2 per mile of road	10.8	10.8

NOTE: One mile of road averaged 32,300 ft^2 of pavement.

Table 10

Comparison of Pavement Smoothness Requirements

Reference	Nation	Pavement	Deviation	Straightedge Length	Place of Measurement
Department of Army (1971)	U. S.	Asphalt roads and streets	0.125 in. (3.3 mm)	10 ft (3.1 m)	Parallel to center line
		Asphalt open storage areas	0.25 in. (6.4 mm)	10 ft (3.1 m)	Parallel to center line
Department of Army (1975)	U. S.	Concrete roads and streets	0.125 in. (3.2 mm)	10 ft (3.1 m)	Parallel to center line
		Concrete storage and parking areas	0.25 in. (6.4 mm)	10 ft (3.1 m)	Parallel and perpendicular to center line
Cement and Concrete Assoc. (1978)	U. K.	Block pavements*	0.4 in. (10 mm)	9.8 ft (3 m)	Parallel to center line
Working Committee on Block Pavements (1965)	GER	Block pavements**	0.3 in. (8 mm)	13.1 ft (4 m)	Any orientation

* Additional requirement: Maximum differential elevation between any two adjacent blocks is 0.08 in. (2 mm).

** Additional requirement: Variation of ±0.3 percent of design lateral grade.

Table 11

Results of Water Penetration Tests (Clark 1979)

Test	Slope %	Paved Area ft^2	Water Application Rate, in./hr	Surface Flow, % of Applied Water	Water Penetration, % of Applied Water*	Length of Test min
1	2.5	32.3	1.81	76	20	60
2**	2.5	32.3	1.77	80	16	60
3	1.0	32.3	2.09	78	18	60
4	1.0	32.3	0.87	70	24	70
5	1.0	32.3	2.05	81	17	45
6	1.0	34.9	1.02	79	21	90
7	1.0	34.9	1.81	80	18	40
8†	1.0	34.9	1.06	77	13	65
9†	1.0	34.9	1.54	83	10	60
10††	1.0	34.9	1.57	89	1	48
11‡	1.0	32.3	1.81	81	15	71

* As determined from measurement at the drainage outlet.
** Repeat of test 1 conducted 28 days later.
† 20 percent clay dust mixed with sand in joints.
†† Same pavement used for tests 8, 9, and 10. Test 10 run 24 hr after tests 8 and 9.
‡ Top soil brushed into surface of joints after construction.

Table 12

Industrial Road Test Section Design (Barber and Knapton 1980)

Item	Subgrade	Thickness of Base Course, in.	Type of Block
1	Sandy clay	11.8	Rectangular
2	Heavy clay	15.7	Rectangular
3	Sandy clay	19.7	Rectangular
4	Sandy clay	23.6	Rectangular
5	Sandy clay	27.6	Rectangular
6	Sandy clay	27.6	Shaped
7	Sandy clay	23.6	Shaped
8	Sandy clay backfill	19.7	Shaped
9	Sandy clay backfill	15.7	Shaped
10	Sandy clay backfill	11.8	Shaped

Table 13

Industrial Road Subgrade Properties (Barber and Knapton 1980)

	Natural Subgrade	Backfill Subgrade	Heavy Clay Subgrade
Applicable test items	1, 3-7	8-10	2
Soil type	Sandy clay	Sandy clay	Heavy clay
Casagrande classification	CL	CL	CL
Plasticity index, percent	15.5	13.5	36.4
Moisture content, percent	12.9	12.3	14.3
CBR, percent	5	3*	2
General quality	Fair to Poor	Poor	Poor

* Remolding upon compaction reduced this to 2 percent.

Table 14

Industrial Road Traffic Deformations (Barber and Knapton 1980)

Item	Base Thickness in.	Traffic Deformation, in.						
		300*	750*	1200*	1500*	1750*	2320*	4070*
1	11.8	0.65	0.63	0.77	0.81	0.83	0.87	0.89
2	15.7	1.08	1.12	1.18	1.18	1.22	1.26	1.32
3	19.7	0.61	0.59	0.71	0.71	0.73	0.83	0.87
4	23.6	0.71	0.73	0.73	0.75	0.79	0.85	0.89
5	27.6	0.43	0.47	0.51	0.55	0.61	0.65	0.69
6**	27.6	0.49	0.49	0.55	0.55	0.57	0.59	0.61
7**	23.6	0.61	0.65	0.67	0.67	0.73	0.73	0.79
8**	19.7	0.67	0.77	0.81	0.83	0.83	0.87	0.91
9**	15.7	1.93	2.05	2.09	2.09	2.11	2.12	0.47†
10**	11.8	3.66	3.98	4.04	4.07	4.13	4.17	0.71†

* Traffic in equivalent 18-kip axles.
** Shaped blocks; all others rectangular.
† Item relaid after 2320 equivalent 18-kip axles.

Table 15

Subgrade and Base Material Properties (Shackel 1979)

	Subgrade	Base
Liquid limit, percent	34.4	--
Plastic limit, percent	16.4	--
Plasticity index, percent	18.0	7.9
Modified AASHTO optimum dry density, lb/ft^3	119.7	124.5
Modified AASHTO optimum moist content, percent	13.0	9.3
In place dry density, lb/ft^3	109.4	118.7
Percent of modified AASHTO dry density	91.4	95.3

Table 16

Summary of Heavy Vehicle Simulator Tests (Shackel 1979)

	Block			Joint Width, in.			Traffic Passes				
Type	Thickness in.	Size in. × in.	Bond	Mean	Max.	Subgrade CBR, %	5400-lb load	8990-lb load	11,240-lb load	13,500-lb load	15,740-lb load
A	2.4	8.9 × 4.4	Herringbone	0.124	0.16	29	--	25,000	10,000	5000	2500
A	2.4	8.9 × 4.4	Stretcher B	0.119	0.16	40	--	25,000	1,000	1000	1000
A	2.4	8.9 × 4.4	Stretcher A	--	--	40	1,500*	--	--	--	--
A	2.4	8.9 × 4.4	Stretcher A	0.109	0.20	9	--	1,000*	--	--	--
B	2.4	8.5 × 4.6	Stretcher A	0.122	0.16	68	--	25,000	10,000	5000	2500
B	2.4	8.5 × 4.6	Stretcher A	0.122	0.16	6	500*	--	--	--	--
C	2.4	8.0 × 3.8	Stretcher A	0.126	0.24	21	--	2,000*	--	--	--
C	2.4	8.0 × 3.8	Stretcher A	--	--	21	13,000	1,300	6,000	3000	2000
C	3.1	8.0 × 3.8	Stretcher A	0.153	0.28	19	--	10,000	--	--	--
C	3.9	8.0 × 3.8	Stretcher A	--	--	6	500*	--	--	--	--
D	2.4	7.9 × 3.9	Stretcher A	0.135	0.28	25	--	500*	--	--	--
D	2.4	7.9 × 3.9	Stretcher A	--	--	25	13,000	6,000	3,000	2000	2000
E	2.4	7.9 × 3.9	Stretcher A	--	--	28	--	2,000*	--	--	--
E	2.4	7.9 × 3.9	Stretcher A	0.126	0.24	9	500*	--	--	--	--
E	2.4	7.9 × 3.9	Herringbone	--	--	9	500*	--	--	--	--

* Failed.

Table 17

WES Block Properties

Property	Test Procedure	Retangular Block	Z Block	Unistone
Absorption, percent	ASTM C 67-78			
5 hr		3.32	2.28	2.60
24 hr		3.93	3.25	3.94
5 hr boiling		6.97	6.11	7.64
Saturation coeficient		56.09	53.18	51.62
Sandblast abrasion coefficient $\left(\frac{cm^3}{cm^2}\right)$	CRD-C 58-78	1.57	2.22	1.72
Freeze-thaw	ASTM C 67-78	-Negligible results-		
Density, lb/ft^3	CRD-C 7-79	139.3	143.8	133.7
Flexural strength, psi	ASTM C 67-78	1,152	1090	1004
Spitting tensile, psi	CRD-C 77-72	1,408	1170	1438
Compressive strength, psi	ASTM C 67-78	10,078	8352	8622

Table 18

WES Field Test Results

Item	Material	Construction Data				Out of Traffic Lane				Inside Traffic Lane			
		Dry Density lb/ft^3	Percent of CE-55	Moisture Content %	CBR %	Dry Density lb/ft^3	Percent of CE-55	Moisture Content %	CBR %	Dry Density lb/ft^3	Percent of CE-55	Moisture Content %	CBR %
1	Crushed limestone	132.5	89.8	3.1	30	132.0	89.4	2.0	46	148.0	100.3	2.1	105
	Clay (surface)	96.3	83.4	25.5	3	95.1	82.3	24.8	6	93.0	80.7	25.2	7
	Clay (4-6 in. below subgrade surface)	93.1	80.6	26.1	3	93.6	81.0	26.0	4	92.3	79.9	26.1	4
2	Crushed limestone	131.2	88.9	3.7	28	144.0	97.6	1.7	33	144.0	97.6	2.1	57
	Gravelly sand	126.4	95.7	7.4	3	122.0	92.4	4.8	6	122.0	92.4	4.0	6
	Clay	92.8	80.3	26.7	3	89.8	77.7	26.3	4	88.5	76.6	26.5	3
3	Crushed limestone	131.7	89.2	3.0	27	135.0	91.5	1.8	18	143.0	96.9	2.6	59
	Gravelly sand	126.2	95.5	5.8	4	122.0	92.4	3.9	4	124.0	93.9	3.7	4
	Clay	93.1	80.6	25.9	3	91.1	78.9	27.3	3	89.6	77.6	27.2	3

Table 19

Average Material Properties

	Crushed Limestone*		Gravelly Sand**		Clay†		Surface of Clay Item 1††	
	Out of Traffic	In Traffic	Out of Traffic	In Traffic	Out of Traffic	In Traffic	Out of Traffic	In Traffic
Dry Density, lb/ft^3								
Mean, lb/ft^3	137.0	145.0	122.0	123.0	91.5	90.1	95.1	93.2
Coefficient of va tion	0.046	0.018	--	--	0.019	0.026	0.016	0.012
Percent CE-55								
Mean, percent	92.8	98.2	92.4	93.2	79.2	78.0	82.3	80.7
Coefficient of variation	0.046	0.018	--	--	0.019	0.026	0.016	0.012
Moisture Content								
Mean, percent	1.8	2.3	4.4	3.8	26.5	26.6	24.8	25.2
Coefficient of variation	0.083	0.127	--	--	0.022	0.020	0.264	0.058
Field CBR								
Mean, percent	32.0	74.0	5.0	5.0	4.0	3.0	6.0	7.0
Coefficient of variation	0.013	0.396	--	--	0.117	0.246	0.091	0.247

* Does not include construction data; 3 measurements for mean value.

** Items 2 and 3; does not include construction data; 3 measurements for mean value.

† Three density, moisture content, and CBR tests per item; 9 measurements for mean value; does not include construction data; does not include surface clay measurements for item 1.

†† Three measurements for mean value.

Table 20

Comparison of Predicted and Actual

Test Section Performance

Item No.	Layer	CBR %	Depth* in.	Predicted** Operations	Equivalent† Depth, in.	Predicted†† Operations	Operations at Failure
1	Base	100	4.1	$>10^9$	6.5	$>10^9$	>8017‡
	Clay crust	7	8.1	3,400	10.5	45,000	
	Clay	4	14.1	22,000	16.5	110,000	
2	Base	100	4.1	$>10^9$	6.5	$>10^9$	>8071‡
	Subbase	20	8.1	2×10^8	10.5	$>10^9$	
	Clay	3	12.1	1,150	14.5	5,000	
3	Base	100	3.4	$>10^9$	6.5	$>10^9$	
	Subbase	20	7.4	2.4×10^7	10.5	$>10^9$	5808
	Clay	3	11.4	3,000	14.5	5,000	

* Actual depth to surface of layer.

** Using actual depth and CBR curves in Figure 78.

† Replace actual block and sand thickness with an equivalent thickness of 6.5 in. (Department of the Army 1979).

†† Using equivalent thickness.

‡ These test sections did not fail.

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121, [13] p. : ill. ; 27 cm. -- (Technical report ; GL-83-3)
Cover title.
"March 1983."
Final report.
"Prepared for Office, Chief of Engineers, U.S. Army under Project No. 4A161102AT22, Task Area AO, Work Unit 005."
Bibliography: p. 117-121.

1. Concrete blocks. 2. Pavements, Concrete. I. United States. Army. Corps of Engineers. Office of the Chief of Engineers. II. U.S. Army Engineer

Rollings, Raymond S.
Concrete block pavements / by Raymond S. Rollings : ... 1983.
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Waterways Experiment Station. Geotechnical Laboratory. III. Title IV. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; GL-83-3.
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